

SPACE OPERATIONS CENTER

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SYSTEM
ANALYSIS

STUDY EXTENSION

FINAL REPORT
VOLUME I

EXECUTIVE SUMMARY

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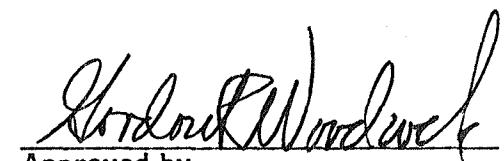
SPACE OPERATIONS CENTER
SYSTEM ANALYSIS
STUDY EXTENSION

Conducted for the NASA Johnson Space Center
Under Contract NAS9-16151, Exhibit B

FINAL REPORT
VOLUME I

EXECUTIVE SUMMARY
D180-26785-1

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Approved by
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SOC Study Manager

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FOREWORD

This executive summary report synopsizes the results of a contracted study of a manned Space Operations Center. The study was an outgrowth of an earlier study conducted at the NASA Johnson Space Center in 1979. The contracted activity began in June of 1980. The initial contract increment covered the period from June 1980 through July of 1981. A set of contract reports were provided to NASA at the conclusion of the initial contract increment. A subsequent contract increment was initiated in August of 1981 and technical work was completed in December 1981. This executive summary report covers the results of both the initial contract increment and the add-on increment. It therefore reflects the results of the entire study.

This study was managed by the Lyndon B. Johnson Space Center. The Contracting Officers Representative and Study Technical Manager was Sam Nassiff. This study was conducted by The Boeing Aerospace Company, Large Space Systems Group with Grumman Aerospace and the Hamilton Standard Division of United Technologies as subcontractors. The Boeing study manager was Gordon R. Woodcock. The Grumman study manager was Ron McCaffrey. The Hamilton Standard study manager was Harlan Brose.

This final report includes five documents:

D180-26785-1	Vol. I	- Executive Summary
D180-26785-2	Vol. II	- Programmatrics
D180-26785-3	Vol. III	- Final Briefing
D180-26785-4	Vol. IV	- SOC System Analysis Report
D180-26495-2		- SOC System Requirements
Rev A		
D180-26495-3		- SOC System Definition Report
Rev A		

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LIST OF ACRONYMS AND ABBREVIATIONS

AC	Alternating Current
CMG	Control Moment Gyro
CO ₂	Carbon Dioxide
DC	Direct Current
DOD, DoD	Department of Defense
ECLSS	Environmental Control/Life Support System
ET	External Tank
GEO	Geosynchronous Earth Orbit
GHZ	Gigahertz
HM	Habitat Module
H _z	Hertz (cycles per second)
IR&D	Independent Research & Development
JSC	Johnson Space Center
LiOH	Lithium Hydroxide
OMS	Orbital Maneuvering System
OTV	Orbital Transfer Vehicle
RFI	Radio Frequency Interference
SOC	Space Operations Center
WTR	Western Test Range (Vandenburg AFB)

1.0 INTRODUCTION

1.1 SUMMARY

This study of a Space Operations Center was conducted in two parts: a Phase A Systems Analysis and a Phase A Extension.

The Phase A study analyzed and defined a manned space station dedicated primarily to operational missions. It developed system design requirements, and design and operational concepts. The reference design developed by the Phase A study is illustrated in Figure 1.

The operational missions included assembly and construction of complex space-craft, servicing and basing of upper stages, and servicing of free-flying satellites. The principal conclusions developed by the study were: (1) a station designed to be launched, assembled, and serviced by the space shuttle would be capable of performing all of the missions and functions identified as probable requirements before the year 2000; (2) Location of operations support facilities should be selected to maximize workspace freedom and flexibility; (3) The station flight attitude best suited to this station design is Earth-oriented; (4) The preferred flight altitude is 370 kilometers, with provisions for raising the altitude during periods of high upper atmosphere density; and (5) A shuttle-supported station should incorporate redundancy and distribution of subsystems and functions to maximize crew safety in the event of accidents or failures. This permits emergency operation in a rescue mode, avoiding a need for an emergency crew return vehicle continuously located at the station.

With these results in hand, the Phase A extension concentrated on development of mission models and analysis of SOC utility. This phase of study considered applications science and technology missions as well as operational missions.

The mission models were founded on budget realities and economic principles. The resulting models are dominated by commercial and DoD requirements. The commercial requirements stem primarily from continued growth of the space communications industry. Materials processing in space is seen as a sizable potential additive requirement. It was so represented in the high model. The DoD

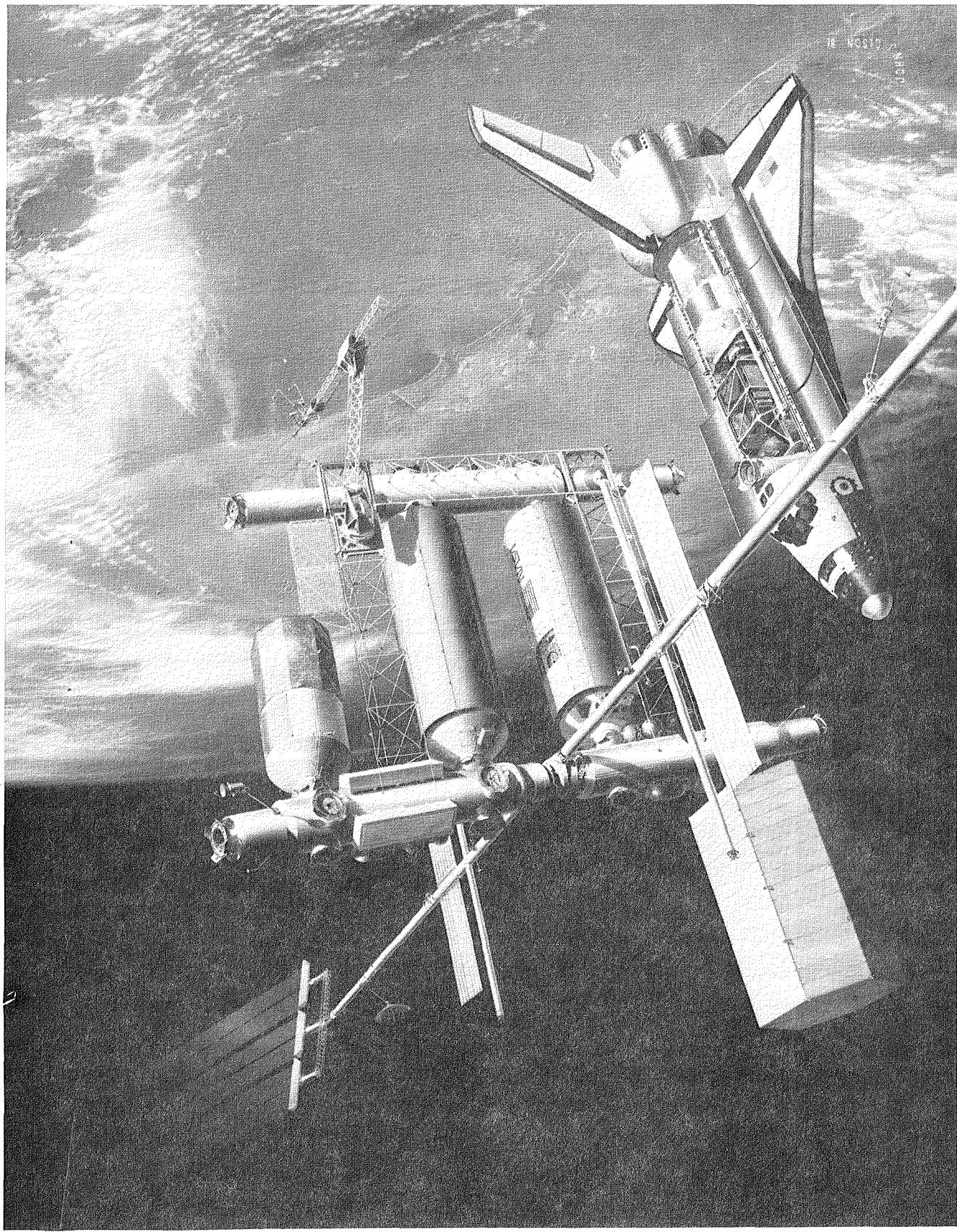


Figure 1. Operational SOC Configuration

requirements stem from DoD spacecraft launches. In the high model, a small DoD manned space station appears in the mid-1990s.

The analysis of SOC operations based on these mission models validated SOC mission needs. SOC mission utility initially serves mainly applications science and technology. Later, it evolves to a major operations support role, including satellite servicing and spacecraft final assembly, test and checkout for large complex spacecraft, space-basing of orbit transfer stages, and decoupling of launch vehicle operations with upper stage operations. A distinct benefit for space basing was identified. A preliminary estimate of SOC cost/benefit ratios was made. These ratios favor SOC development.

As anticipated, an evolutionary program is the best fit to the mission needs. The initial need, for the low and median traffic models, is for two to four people with a growth to 12 to 20 people by the year 2000. The high mission model exhibits somewhat greater initial needs and grows to a need for more than 50 people in space by the year 2000.

In order to reduce peak funding for system development, we developed an initial configuration that can be implemented with a single module design. This module is outfitted as a habitable service module and can be modified to serve as a resupply module. Two of these habitable service modules provide a space station adequate for a crew of four, with the requisite redundancy, and capable of accommodating the early mission requirements. Habitat modules can be added to this system later for growth from an initial capability of four people to a later capability of 12. The modular approach also offers improved system versatility over earlier concepts.

1.2 PROGRAM OBJECTIVES

The following program objectives were derived from the results of the mission needs and programmatic analyses of the Phase A contract extension.

The Space Operations Center Program should:

1. Establish a program for the evolutionary development of permanent manned facilities and operations in near-Earth space with growth potential to high-energy orbits.
2. Implement a versatile modular system to satisfy a broad range of potential missions, including applications science and technology, operational support of present and future space transportation systems; servicing of satellites and space platforms; deployment, assembly or construction of space systems and space structures; and potential military uses of manned space systems technology.
3. Establish an initial capability based on the design of a single Shuttle-compatible module that can be used in a pair configuration to support four people (it could be used in a single-launch configuration to support two or three people). This initial module should be designed to facilitate addition of other modules and facilities, to grow to a system with up to 12 crew, capable of supporting all the mission application cited in (2) above.

Key features of the program plan should include the following:

1. The system should employ advanced technology, especially in the areas of data management, communications, environmental control and life support and electrical power. The use of advanced technology will provide a long useful life without obsolescence. The system should be designed to accommodate incremental growth and improvements in technology commensurate with the evolutionary nature of the program.
2. The plan should include technological development of high-leverage operational capabilities such as space-basing of upper stages and zero-g transfer of cryogenic propellants. These technological features should be incorporated so that experimental demonstrations can grow smoothly into operational capabilities.

3. The basic system element designs should be compatible with modular incremental expansion, over a 10 to 20 year operational life period, to facilities capable of housing at least 20 people.
4. The program plan should make maximum synergistic use of government and industry facilities and capabilities to achieve the most rapid capability growth possible commensurate with funding limitations and evolution of mission needs.

1.3 BACKGROUND

Concepts for permanent habitable facilities in orbit date back to the earliest times in which space flight was recognized as technically possible. Engineering concept studies for such facilities by NASA date from before the first Mercury manned space flights. Studies of space stations have continued throughout the U.S. space program. A military space station project, the Manned Orbiting Laboratory, was initiated in the late 1960s and later cancelled for lack of a clear-cut mission. In the early 1970s, NASA launched and operated an interim space station, the Skylab, developed from hardware and systems available from the Apollo Manned Lunar Landing Program.

In the early 1970s, NASA carried out extensive design studies for space stations in parallel with the design studies for the Space Shuttle. These studies were carried through the Phase B process and included extensive mission applications analyses for scientific missions to be conducted onboard.

Funding limitations necessitated a choice by NASA between development of the Space Shuttle and of a space station. NASA elected to develop the Space Shuttle.

During the middle to late 1970s, additional Phase A studies of space stations were conducted. During the same period, conceptual studies sponsored by the Department of Energy investigated the feasibility of establishing large solar power stations in space. These and other projects, about which there has been considerable speculation in the last several years, would necessitate the accomplishment of construction projects in space.

As interest developed in potential applications of space construction for fabrication of large spacecraft projects for communications, scientific, and other purposes, design trends for permanent, habitable facilities in space began to depart from the scientific laboratory concept, toward meeting operational needs such as space construction, space-basing of upper stages, space test and checkout of complex satellites, and the mating of upper stages to spacecraft for transfer to mission orbits.

In 1979, studies of the Space Operations Center were begun at NASA JSC. A conscious decision was made to limit initial mission applications to operational functions. Accordingly, the initial missions specified for the Space Operations Center were 1) space construction (fabrication or assembly of large spacecraft), 2) servicing of free-flyer spacecraft, and 3) flight support, i.e., serving as an element of the space transportation system, i.e., as a station to which Shuttle payloads and propellants could be delivered. The payloads would be assembled, tested, checked out, mated to upper stages, and the upper stages refueled from propellant storage, launched to destination orbits, and recovered for reuse. The present contracted study was initiated with these mission definitions for the Space Operations Center.

1.4 WHY MAN?

The recommendation that a manned space station be placed in orbit to serve operational functions and to conduct applications science and technology missions raises anew the old issue of man versus "robot". In principle, of course, any specific crew activity to be performed on board the Space Operations Center could be automated. Some would be exceedingly difficult and expensive to automate, but none appear entirely beyond the state of the art.

The reason for man is not that automation of the functions to be performed is impossible, but simply that accomplishment of these functions by a flight crew is the most practical and lowest-cost means of getting them done.

An examination of SOC crew operations reveals that these operations are not routine and repetitive. Typical crew tasks, such as servicing a satellite or preparing an upper stage for launch, require twenty to forty man-days of crew

effort. These jobs are similar from one occurrence to the next, but not identical. No two servicing events will be alike, nor any two upper stage servicing tasks. The applications science and technology missions identified as most appropriate for SOC are those needing frequent crew intervention. The outcome of these experiments cannot be entirely predicted in advance. The continuing experimental program must be planned in real time. We anticipate that the need to respond to unexpected situations will be commonplace.

The cost of a man-day of crew labor onboard the SOC was estimated during the study. Including amortization of the investment in the SOC facility, as well as resupply and crew operations, the cost is \$135,000 per man-day. Consequently, the cost of crew support for a representative job is in the two-to-five-million-dollar range. Although we did not develop a directly comparable automated system approach, it appears that equivalent automated functions could be provided only at much higher cost. It is not at all clear how an automated approach could respond to unexpected events. It is not even clear that the software alone, for an automated approach, could be developed at a competitive cost.

The SOC system design has not overlooked automation. It relies extensively on automation to relieve the crew of performing functions that are readily automated. The resulting data management system concept represents one of the most ambitious automation systems yet conceived, with many interconnected advanced microprocessors and several million bytes of executable code.

2.0 MISSION MODELING AND UTILITY ANALYSIS

2.1 RELATIONSHIP TO OTHER TASKS

An exclusively operational design approach was retained for the first several months of the Phase A study. This permitted definition of operational requirements and facilities, and determination of the influence that these functions would have on the design of a manned space station. A relatively thorough configuration understanding was developed, as described in Section 3 under the discussion of trades and options. The configuration presented earlier in Figure 1 resulted from this study activity.

As this initial work was being conducted, we began to develop an interest in broader applications of the Space Operations Center and in the relative merits of all-up versus evolutionary programs. In response to these issues, we conducted an initial mission needs analysis on Boeing IR&D to develop a better perspective on the utility of the Space Operations Center. This analysis was based on a mission traffic model developed by Boeing for NASA under the Orbit Transfer Vehicle Phase A studies. That model, because it was intended for OTV studies, left out things important to the Space Operations Center studies, e.g. satellite servicing missions in low Earth orbit and science and applications missions that might be conducted on board the SOC.

During this time, it became clear that some of the science and applications missions contemplated for a manned space station were of immediate practical concern. These missions included life sciences research intended to enhance capabilities for long-term manned space flight; materials processing research aimed at development of commercial processes for production of special materials in micro-gravity; and the use of a manned space station to conduct instrument and technology testing now conducted at higher cost on free-flyer spacecraft (and planned for shuttle sorties). Recognition of a need for more thorough mission and utility analyses continued to grow throughout the initial study increment.

In the latter half of the Phase A study, concepts for evolutionary development and use of the Space Operations Center were developed, based on the modules defined

for the all-up system. A number of ways in which these modules could be used for incremental build-up were defined. Most of the effort during this period was devoted to subsystems analyses and definition.

At the conclusion of the Phase A study, a recommendation was made that the Phase A extension concentrate on mission needs analysis and alternative applications of the SOC and of its technology. In parallel, a broader look at programmatic and design options was to be undertaken.

2.2 MISSION MODELING APPROACH

A major part of the Phase A extension was devoted to mission modeling and analysis, expanding on the initial mission needs analysis conducted during the earlier study increment. A part of this task was to develop a fresh approach to mission modeling, one based on economic principles.

Past attempts at mission modeling have relied mainly on survey methods. These have not proven very successful. The reasons for lack of success vary. The economic sectors of the space economy have different characteristics.

The first sector considered in our analysis was the NASA research and applications spacecraft sector. This sector is comprised of research and applications, including astrophysics and solar terrestrial physics, planetary exploration, etc. It is characterized by budget levels that have become institutionalized. Although these levels are subject to variation depending upon political trends and problems with Federal deficits, a long-range forecast must presume that current budget pressures will not permanently reduce the institutionalized levels of research.

In this sector, past mission models have presented lists of payloads for which scientific or applications rationale exists, but lists that do not consider the budget realities that will constrain the number of payloads developed and flown.

The second sector of our model is comprised of that category of research that would be carried out on a manned space station, should one become available. A review of many potential lines of research indicated that the ones most likely to be implemented would be life sciences and materials processing, with some

additional activity in space technology testing. There is no well-organized constituency for this research since no research facility has been available.

The life sciences community is presently planning Spacelab applications. There is some literature for utilization of a permanently-manned facility; it was used as a source in this study. Materials processing researchers are presently considering mainly shuttle sortie flights and free fliers. The substantial opportunities that would exist with a manned space station have not been well represented in the available literature.

This sector is characterized by latent demand. Budget levels for flight research are not institutionalized. Present funding for life sciences and materials processing within NASA is modest. It is plausible to anticipate some increase in budget levels with the availability of a manned space station, but because of continuing pressure on the Federal budget it is not expected that these areas would become heavily funded. Private sector funding is available for materials research. The amount is not known, but is potentially significant. Major industrial sectors of the economy could benefit from breakthroughs in micro-gravity materials processing.

The commercial sector exploits space operations that are profitable. Presently, this sector is confined to communications, using satellites. Commercial sectors are characterized by exponential growth. In the case of space communications, the rate of growth has been quite rapid. A future potential exists for materials processing commercial production if suitable processes are developed.

In the commercial sectors, the typical planning horizon is relatively short, with the emphasis on near-term profitability and cash flow characteristic of a commercial organization. Long-term plans that may exist are generally treated as business secrets and are not revealed to anyone who surveys these organizations.

The final sector is the defense sector. This sector is driven by estimates of the military threat, and to some degree by perceived military opportunities. Historically, this sector has exhibited a continued gradual increase in budget. Projection of present trends would suggest a budget doubling before the year 2000.

The defense sector exhibits less of the "wish list" syndrome than the NASA sector, inasmuch as the planning process in DOD is more inclined to take into account budget realities. The defense sector also tends towards a planning horizon of about 10 years. In an unclassified study, the classification of specific projects, and the sensitivity of revealing evolution of policy through forecasting of specific missions, precludes direct use of most of the official planning data.

Three mission models were created in order to bound the range of plausible futures. The models incorporated the following economic and budgetary assumptions:

Low Model—Highly Conservative Projections

NASA Research: Continued Gradual Decline in Real Budget Authority

Commercial: Less Growth Than Present

DoD: Cessation of Historical Growth Trends

Median Model—Most Likely Projections

NASA Research: Roughly Constant Real Budget Authority

Commercial: Continuation of Present Trends

DoD: Continuation of Present Trends

High Model—Optimistic Projections

NASA Research: Gradual Increase in Real Budget Authority

Commercial: Modest Increase in Present Growth Rate

DoD: Increase in Present Growth Rate

2.3 MISSION MODEL RESULTS

Research and Applications

The NASA research and applications mission model was developed by a rationalization procedure, beginning with available models created by a survey approach.

The available models were assumed to represent scientifically-justifiable missions.

Our basic premise was that each subsector of the NASA Research and Applications sector would maintain roughly its historical budget levels. A high-level cost model, derived from historical experience, was employed to derive budgetary estimates for spacecraft development, production, reuse, and servicing. It was presumed that the cost of spacecraft development and production will dominate funding requirements; ignoring launch services costs should not invalidate in the model.

The astrophysics subsection of the research and applications sector is representative. Figure 2 presents the estimated funding requirements for the near-term astrophysics programs described in NASA planning documents.

The long-range programs reached even higher levels with a funding peak in the mid 1990s of roughly \$1½ billion as shown in Figure 3.

This program, as presented, is characterized by multiple simultaneous development of observatory-class payloads. It must be regarded as unrealistic inasmuch as the present level of annual funding for the astrophysics programs is on the order of \$200 million. Consequently, the final model eliminated or deferred developments so that a program funding projection similar to historical budget trends was realized.

The astrophysics model, after being rationalized, exhibits the funding trend illustrated in Figure 4. This was used as the median traffic model. The low traffic model had fewer payloads and the high traffic model slightly more. The differences between the low and high models were not great inasmuch as the institutionalized nature of these sectors would suggest that large fluctuations in historical funding trends should not be expected. Similar results were developed for other components of this sector.

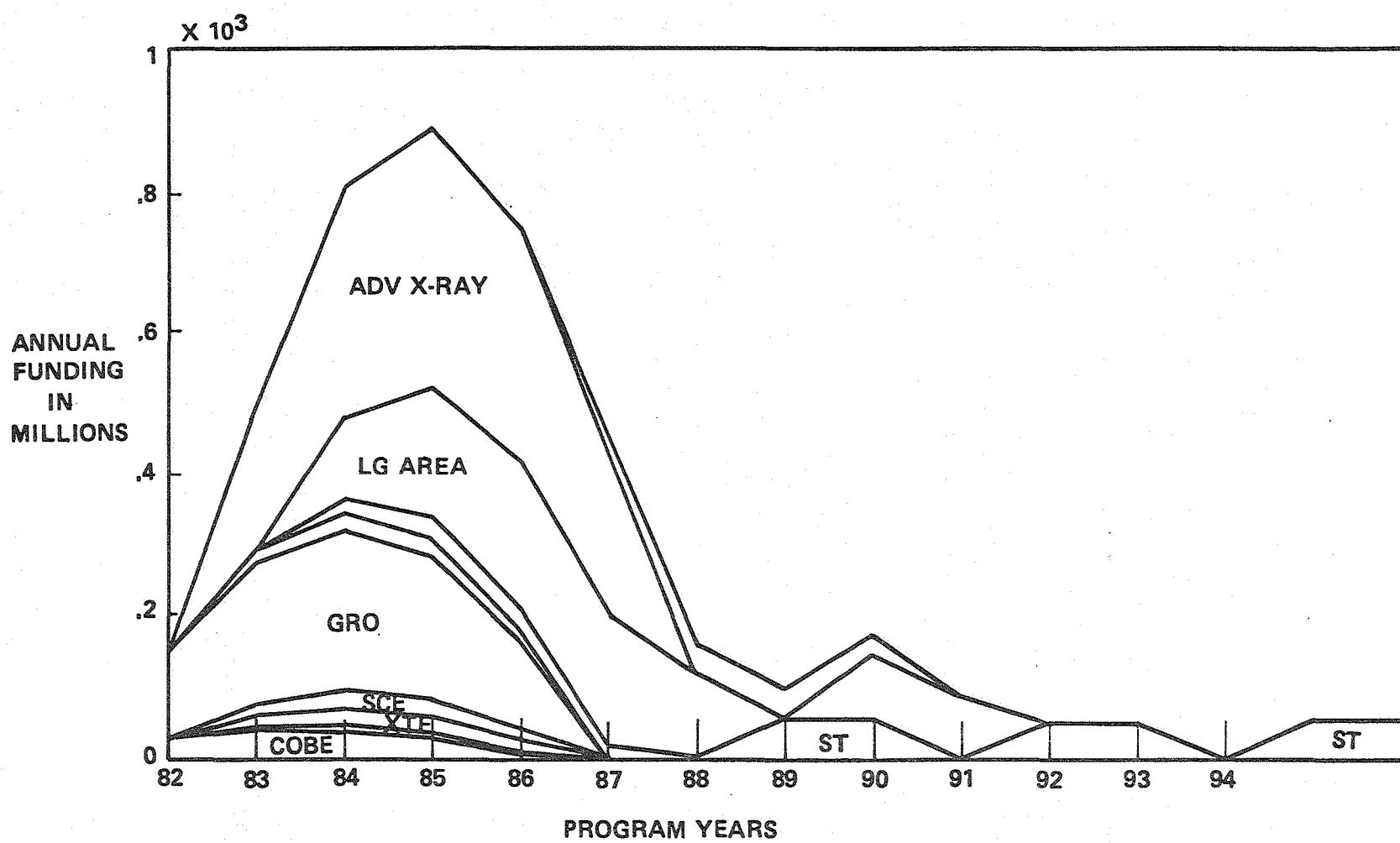


Figure 2. *Astrophysics Funding Levels
(Near-Term Programs
as Presented in NASA Planning Documents)*

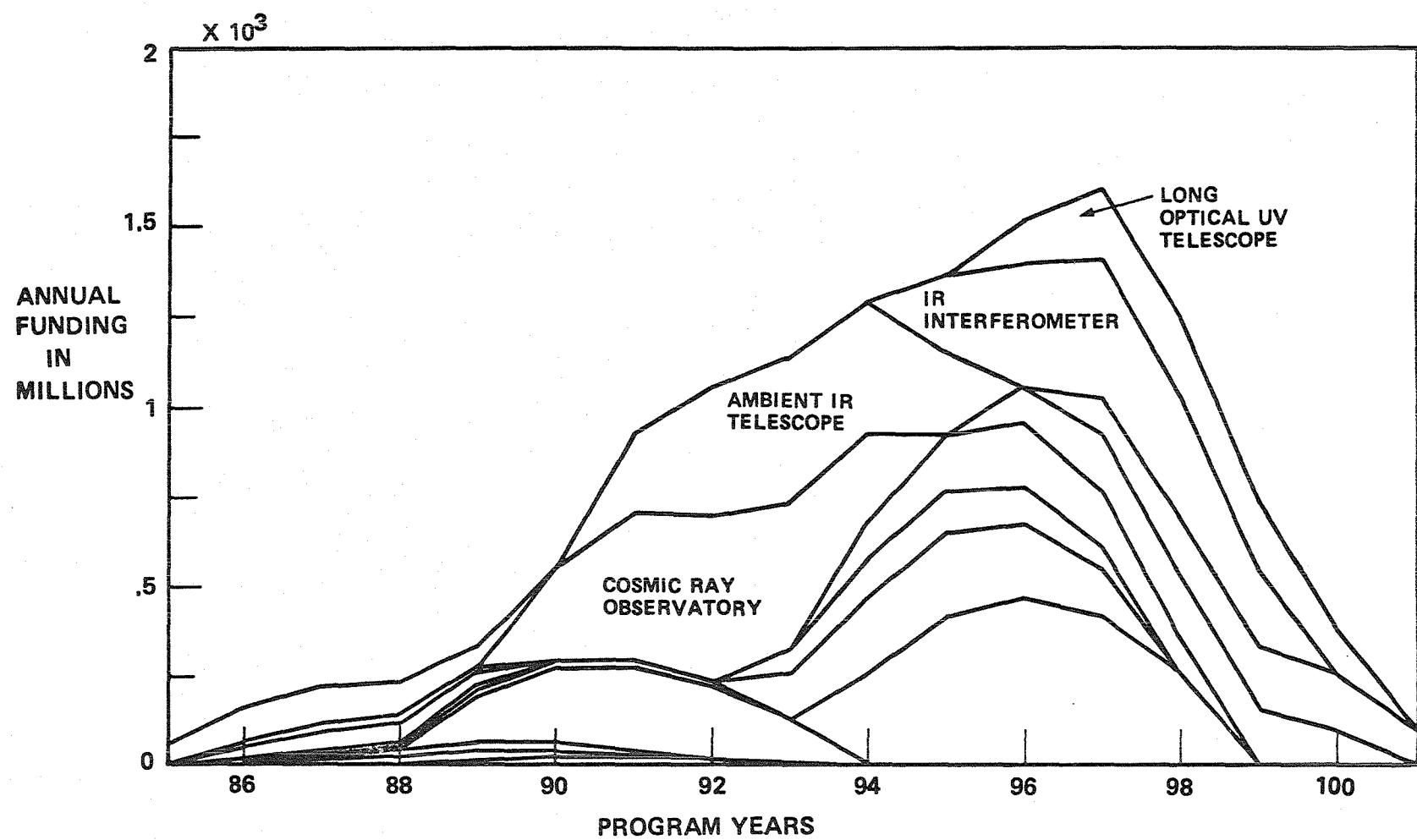


Figure 3. Astrophysics Funding
(Long-Range Programs
as Presented in NASA Planning Documents)

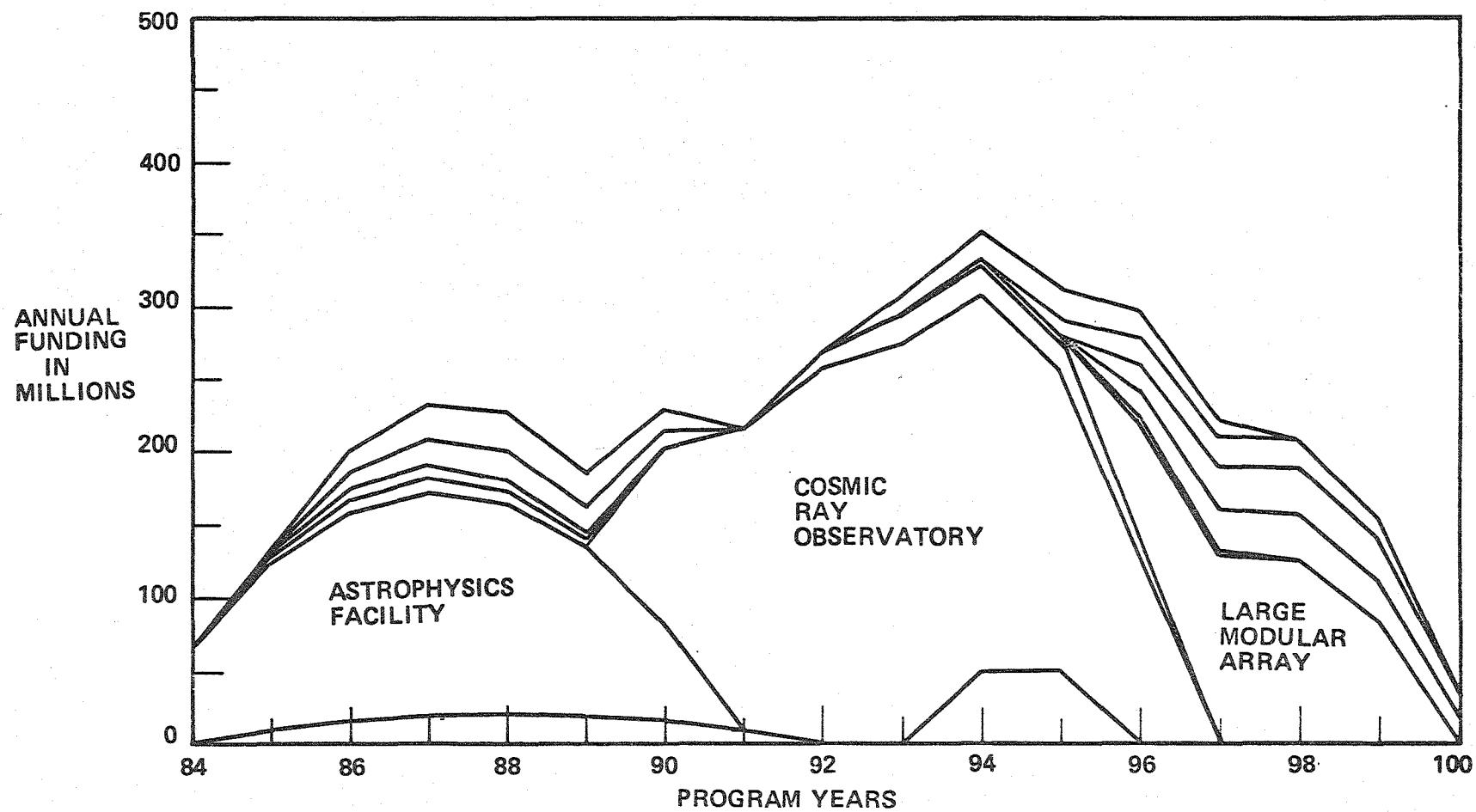


Figure 4. Rationalized Astrophysics Model
(Based on Medium Traffic Model)

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Onboard Applications Science and Technology

Three representative mission categories were analyzed in the onboard applications science and technology sector. These were life sciences, materials processing, and DoD and technology space testing of subsystems, instruments and technologies.

A review of research recommendations from the space station studies of the early 1970s suggested that mission activities in other areas such as space physics and communications would be relatively insignificant and not worth the investment of time and effort to create mission models. These kinds of activities can generally be aggregated under the DoD and technology category.

Only limited aspects of life sciences research can be investigated on short duration space missions. The existence of a manned space station would permit research on long-term exposure to the space environment for meaningful time periods. The flexibility of a permanently-occupied station would enable operation in a laboratory mode. This would offer the flexibility of in-situ modifications of experiment protocols, and the introduction of new and varied experiments as the research evolves. It would provide the opportunity for repairs if malfunctions occur.

Three models were created for life sciences research, as was the case for the other sectors. The low model satisfies those research objectives most essential to routine long-term manned space operations. These research objectives would be essential, for example, to manned military space systems.

The median model included additional research objectives of a more academic nature; objectives related to understanding the effects of micro-gravity, and other aspects of the space environment, on a variety of living organisms. These research objectives will have practical applications in the future. The well-being of other living organisms in space will eventually be important to permanent space settlements.

The high model was designed to satisfy all presently identified micro-gravity life sciences objectives, excepting those requiring a human centrifuge. (The human

centrifuge is an unreasonable requirement to impose on a space station in the SOC class.) Note that even the high model does not address research objectives that might be identified in the future. Future objectives of high priority will displace objectives presently recognized, but of lower priority.

Figure 5 summarizes the life sciences mission models in terms of the number of space station crewmembers dedicated to this type of research.

The field of micro-gravity materials processing is presently in an early research stage. This research has been carried out on past space missions as well as in aircraft, drop towers and sounding rockets. A number of such experiments are planned for Shuttle and Spacelab flights in the 1980s.

Process development will, in the future, use commercial risk capital to develop proprietary processes that will return profits when the process is fully developed and commercialized. These process developments must be expected to reach a successful conclusion in relatively few years. Otherwise, they will not be sufficiently attractive to merit a risk capital investment. A continuously-manned space station is expected to reduce process development time to the point of commercial attractiveness. Process development time on a space station would not be greatly more than a comparable process development on Earth.

Our low model for materials processing is an extrapolation of present Spacelab research plans. The median model assumes that the existence of a manned space station would stimulate additional research activity over that planned for Spacelab, and that process development could begin in 1992.

The high model represents a moderately aggressive program to develop commercial processes. Process development begins in 1991. Four parallel process development activities are in progress by 1995. The first commercial production free-flyer is launched in 1998.

Figure 6 presents a summary of the DoD and technology space testing models. These represent continuations of present trends in space testing. The Space Operations Center would provide services now provided by spacecraft buses, and to be provided in the future by the shuttle. The crew would provide experiment

SOC-1394	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00
<u>LOW MODEL</u>																
MEDICAL RESEARCH	.1	.1	.1	.1	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5
SUITCASE EXPERIMENTS	.1	.1	.1	.1	.1	.1	.1									
SPACE AVAILABLE EXPER.								.2	.2	.2	.2					
DEDICATED LS MODULE	*	*	*	*								1	1	2	2	2
<u>MEDIUM MODEL</u>																
MEDICAL RESEARCH	.1	.1	.1	.1	.5	.5	.5	1	1	1	1	1	1	1	1	1
SUITCASE EXPERIMENTS	.1	.1	.1	.1	.1	.1										
SPACE AVAILABLE EXPER.							.2	.2	.2							
DEDICATED LS MODULE	*	*	*	*							1	1	2	2	2	2
RES. CENTRIFUGE MODULE												.5	.5	.5	1	1
<u>HIGH MODEL</u>																
MEDICAL RESEARCH	.1	.1	.1	.1	1	1	1	1.5	1.5	1.5	1.5	1.5	1.5	1	1	1
SUITCASE EXPERIMENTS	.1	.1	.1	.1	.1	.1										
SPACE AVAILABLE EXPER.																
DEDICATED LS MODULE	*	*	*	*				1	2	2	2	3	3	3	3	3
RES. CENTRIFUGE MODULE												1	1	1	1	1
DEDICATED CELSS MODULE																2

*CREW INVOLVEMENT BASED ON 1 SHUTTLE/LS SPACELAB MISSION PER YEAR.

Figure 5. Life Sciences Mission Model
(Crew Involvement in Manyears/Year)

- CONTINUATION OF PRESENT TRENDS IN SPACE TESTING
- SOC PROVIDES THOSE SERVICES NOW PROVIDED BY SPACECRAFT BUS OR SHUTTLE
- EXPERIMENT-TENDING OPERATIONS

	89	90	91	92	93	94	95	96	97	98	99	00
LOW MODEL MAN LEVEL	0.1	0.1	0.1	0.1	0.2	0.1	0.2	0.1	0.2	0.1	0.2	0.1
MEDIAN MODEL MAN LEVEL	0.2	0.2	0.7	0.3	0.7	0.7	0.7	1	1	1	1	1
HIGH MODEL MAN LEVEL	0.2	0.2	0.7	0.3	1	1	1	1	1	1	1	1

Figure 6. DoD and Technology Space Testing

tending. These experiments would ordinarily be mounted on pallets and berthed to a Space Operations Center berthing port.

Commercial

The model for the commercial communications sector was derived from an economic-technical rationale based on historical experience and technological projections.

New technologies introduced to the marketplace often stimulate a high rate of growth over one to three decades. Lower costs of the new technology cause rapid acquisition of a significant market sector for whatever service or product is offered, and rapid economic growth occurs. A review of historical data indicated that as many as four growth periods exist: infancy (very rapid growth); adolescence (rapid growth for one to three decades) maturity (growth roughly paralleling the U.S. gross national product for several decades), and obsolescence (leveling or decline in output). Figure 7 compares a schematic representation of the phenomena with an actual historical case: the number of voice telephones installed in the U.S.

Our space telecommunications model combined a range of economic growth projections with technical and cost projections of improvements in the technology. Figure 8 presents the variations in the most important parameters in the model. Most of the growth in assets value is expected to occur in the ground-based segment of the systems. The fractional value of the space segment is projected to decline to 10% to 20% of the total by the year 2000. The cost and mass per equivalent transponder is also expected to decline.

Spacecraft are expected to become larger and last longer. The U.S. share of total telecommunications launches is expected to decline as foreign competition becomes stronger.

The resulting models for delivery of telecommunications spacecraft are shown in Figure 9. They were completed by translating parametric trend forecasts into specific numbers of spacecraft of different sizes to be launched each year. The progression to larger spacecraft was forecast to be gradual, with a larger

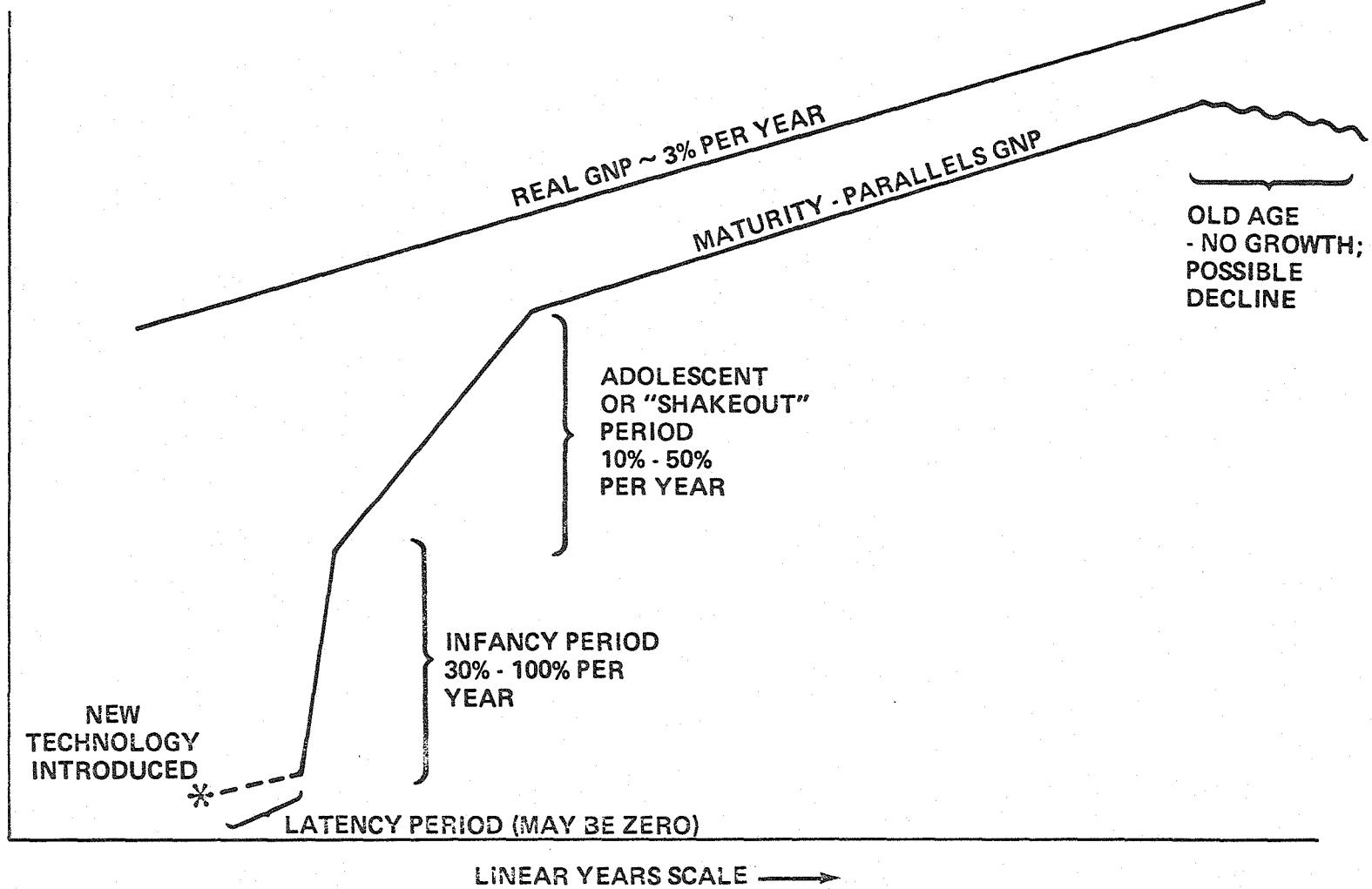
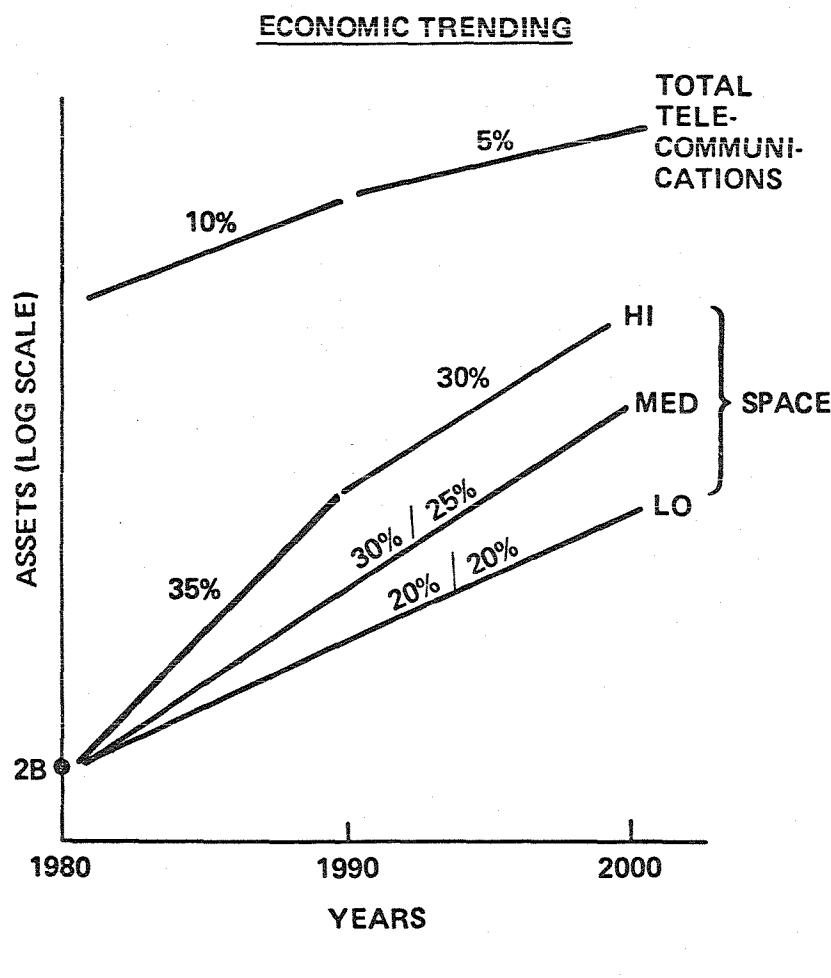
LOGARITHMIC
MARKET
SCALE

Figure 7. The Economic Trending Concept



VALUE, 1980	MODEL ELEMENTS		
	LOW	MED	HIGH
VALUE OF SPACE SEGMENT, % OF TOTAL			
50%	20%	10%	10%
SPACECRAFT COST, \$/kg			
25000	14500	13500	10000
SPACE TRANSPORTATION COST, \$/kg			
20000	11000	7200	5000
PAYOUT MASS PER TRANSPONDER			
10 kg	3	3	3
BUS/PAYOUT RATIO			
3	2	2	2
REPRESENTATIVE S/C MASS			
1000 kg	3000 Kg	4000 Kg	15000 Kg
REPRESENTATIVE S/C LIFE			
7 YR	15 YR	15 YR	15 YR
100% U.S. MARKET SHARE OR TOTAL TELECOM. LAUNCHES			
	50%	50%	50%

Figure 8. Space Telecommunications Model Concept

		CALENDAR YEAR																			
		81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00
		MASS (TONNES)																			
HIGH MODEL	1	5	3	5	5	5	4														
	2	2	2	3	3	4	4	4	3	10	10	5	6	10	10	7	5	8	7	5	
	3				1	2	5	9		2	5	2	5	10	5	7	5	8	7	5	
	4																				
	5																				
	7																				
	10																				
	TOTAL	5	5	7	8	9	10	9	12	12	15	13	15	17	19	20	22	26	30	33	38
MEDIAN MODEL	1	5	3	4	3	3	5	2	2												
	2	1	1	2	3	3	4	5	2	6	9	6	8	8	7	8	6	11	14	12	15
	3					1	2	1	2	6	1	1	1	2	3	4	6	11	14	12	15
	4																				
	7																1	1	2	3	4
	TOTAL	5	4	5	5	6	8	7	9	8	9	7	9	10	10	12	13	14	16	15	19
LOW MODEL	1	3	2	2	3	3	4	3	4	3	2										
	2	1	1	1	2	2	2	3	3	3	1	5	5	5	3	7	6	7	8	9	11
	3										1	1	1	3	3	1	7	6	7	8	9
	5																1	2	3	4	
	TOTAL	3	3	3	4	5	6	6	7	7	8	6	8	8	8	7	9	10	11	12	15

Figure 9. Telecommunications Models

spacecraft introduced every two to five years, as true in the past. The high model grows to larger spacecraft than the median or low models. As many as three different classes of spacecraft are launched simultaneously in some years. This also is typical of the past.

Defense

Official DoD planning data cannot be directly utilized in the creation of an unclassified military mission model because they are classified. These plans also do not predict far enough into the future for a SOC mission model in which payload activity would begin about 1990. Unclassified sources do permit projection of general types of missions and level of activity.

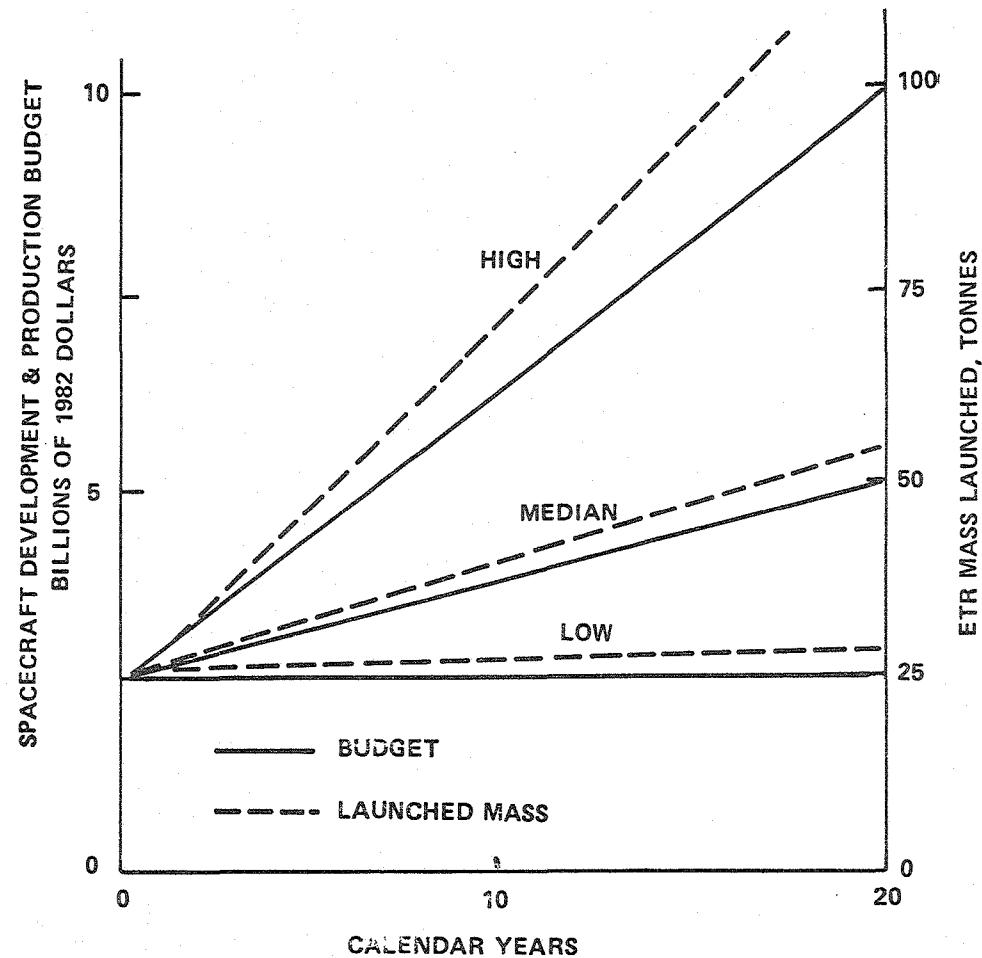
We developed a budget-driven model that we feel is realistic. Three levels were developed: low, median and high. We did not consider WTR launches except in our projection of the total demand for space transportation.

Figure 10 presents the budgetary assumptions used in the military model. The low model assumes a cessation of historical growth in military space spending, the median model projects a continuation of historical trends, and the high model presumes increased growth with new classes of military missions. The derived mission models for the three military model levels are presented in Figure 11.

2.4 UTILITY ANALYSIS

Figure 12 presents a summary of the high, median, and low mission models. They are dominated by the commercial communications and defense sectors.

These mission models are forecasts of mission events or operations to be accomplished each year in a U.S. space program. Since one of the functions of SOC is to serve as an element of space transportation systems, it is necessary to understand the space transportation requirements imposed by the mission models. To prepare for the SOC utility analysis, we converted the mission models into transportation traffic models.



- LOW MODEL
 - NO SIGNIFICANT CHANGE IN USES OF SPACE
 - GRADUAL GROWTH OF AVERAGE SPACECRAFT MASS TO 5000KG BY END OF CENTURY
- MEDIAN MODEL
 - ASAT THREAT LEADS TO BUDGET GROWTH FOR SPACE DEFENSE
 - SPACECRAFT MASS GROWTH SAME AS LOW MODEL
 - MANNED ACTIVITY ONLY FOR SPACE TESTING AT A NATIONAL SPACE STATION
- HIGH MODEL
 - SPACE EVOLVES TO THEATER OF CONFLICT
 - SPACECRAFT AVERAGE MASS GROWTH TO 10,000 KG
 - SMALL MILITARY MANNED

CALENDAR YEAR												
<u>LOW</u>	89	90	91	92	93	94	95	96	97	98	99	200
1-TONNE CLASS	3	2	2	2	2	2						
2-TONNE CLASS	4	3	3	3	3	3	2	2	2	2	2	2
3-TONNE CLASS	3	3	3	3	3	3	3	3	3	3	3	3
<u>MEDIAN</u>												
1-TONNE CLASS	3	2	2	1	1							
2-TONNE CLASS	6	5	5	5	5	4	4	4	3	3	2	1
3-TONNE CLASS	6	5	5	4	4	5	3	3	2	2	2	3
5-TONNE CLASS		2	2	3	4	4	5	5	5	6	5	5
10-TONNE CLASS									1	1	2	2
<u>HIGH</u>												
1-TONNE CLASS	3	2	2	1	1							
2-TONNE CLASS	6	5	5	5	5	4	4	4	3	3	2	1
3-TONNE CLASS	6	5	5	4	4	5	3	3	2	2	2	3
5-TONNE CLASS		4	4	6	8	8	6	6	8	10	10	10
10-TONNE CLASS				1	1	1	2	2	2	3	4	4
MANNED STATION							1	1				
MANNED STATION								2	4	4	4	4
RESUPPLY												

NOTE: SPACE TESTING AT SOC NOT INCLUDED IN THESE PAYLOADS

Figure 11. Military Mission Models

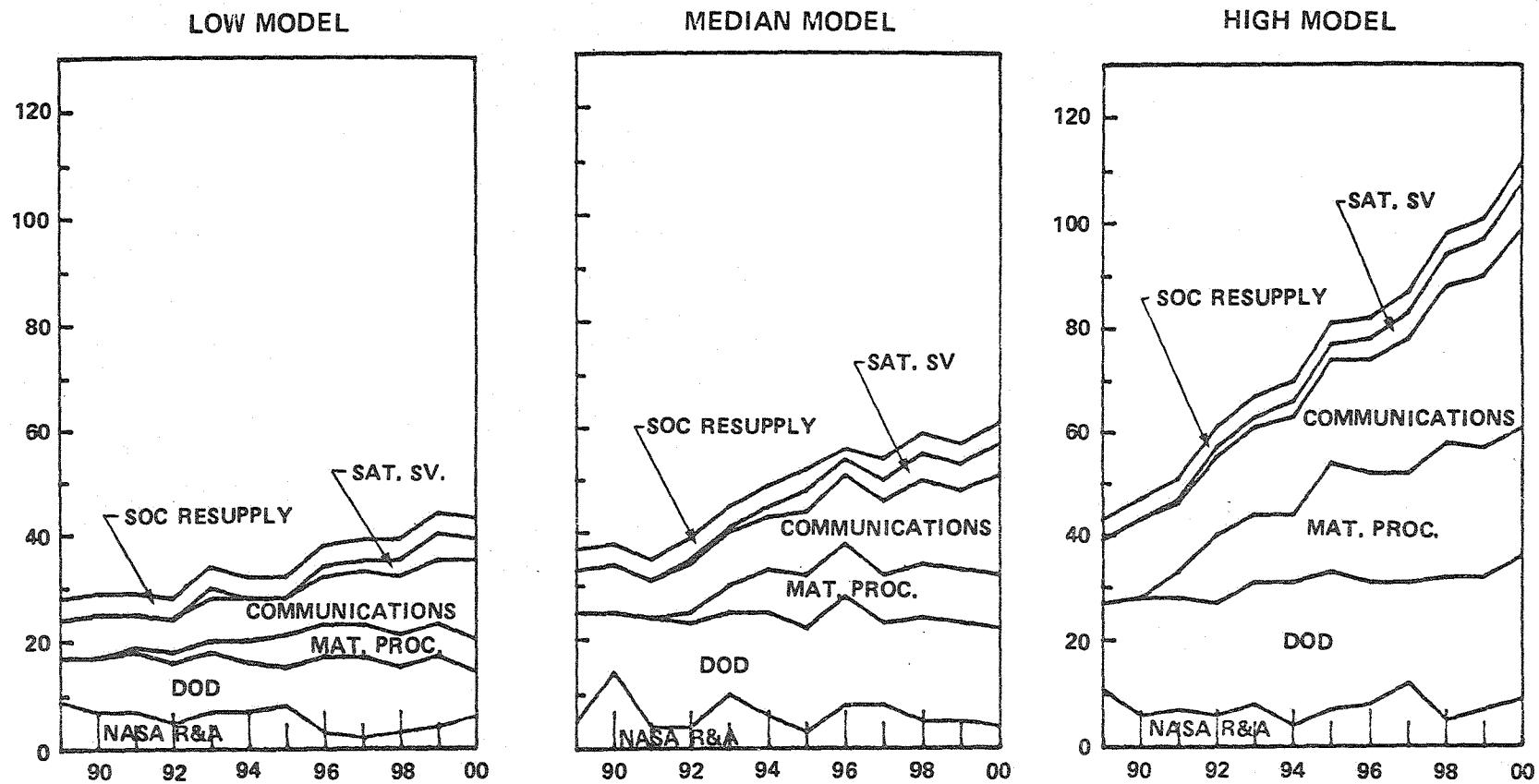


Figure 12. Comparison of the Mission Models

The traffic models were created by calculating the space transportation traffic needed to accomplish each of the mission models. The SOC utility analyses were then conducted to identify necessary SOC operations, and crew skills and manning levels for the three mission models and a range of transportation options. The general logic is shown in Figure 13.

We employed a manifesting code that analyzes each traffic model year-by-year and mission-by-mission. At user option, either ground or space-basing of the orbit transfer vehicle (OTV) can be selected. In either case the first step is to select an appropriate OTV mode if an OTV is required.

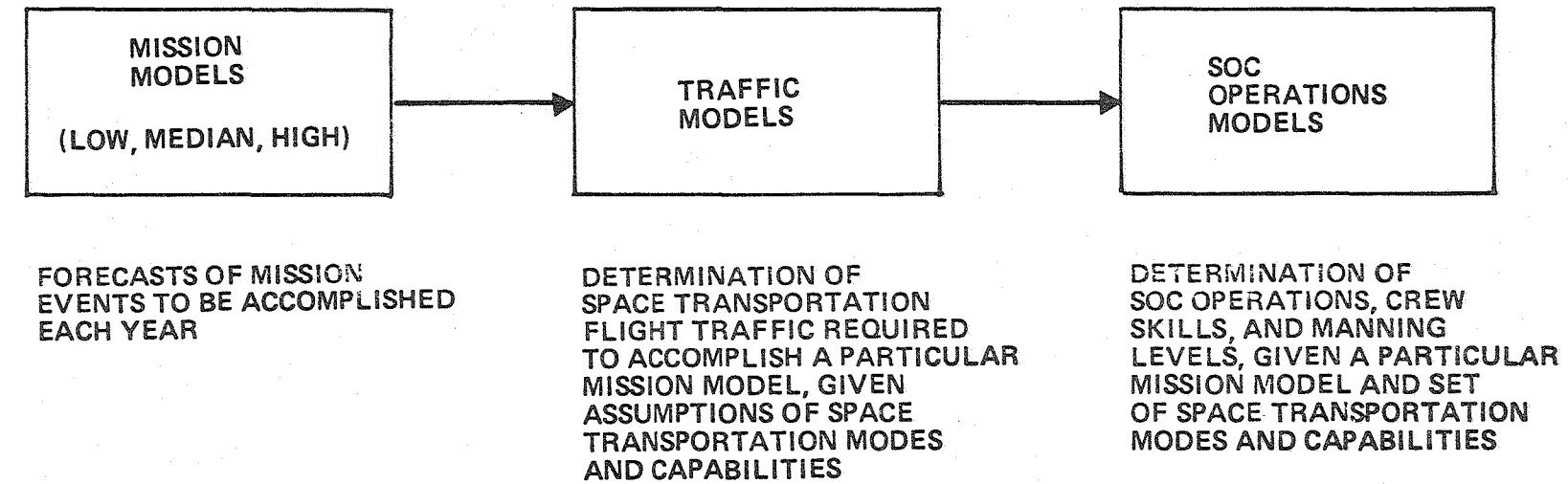
The manifesting logic selects from among nine ground-based OTV staging and reuse modes, or five space-based modes. The mode for each mission is selected to provide the least cost, considering Shuttle and OTV costs.

Aerobraking operations are simulated by adjusting the delta v and the inert weight of the OTV to represent the delta v savings of the aerobraking pass and the added inert weight of the aerobraking equipment.

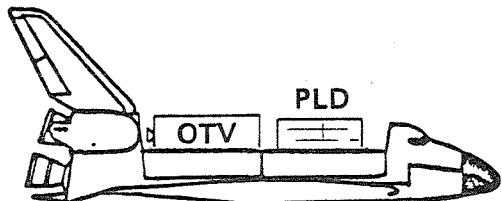
The ground-based OTV manifesting logic is shown on the left of Figure 14. Whenever possible, a payload is manifested with its own OTV in a Shuttle flight. If necessary, the OTVs and payloads are manifested separately, in which case these OTVs and payloads pass through a grouping logic to improve shuttle manifesting whenever possible.

The center diagram shows the space-based manifesting logic used in the first part of the SOC study. This algorithm manifested payloads together whenever possible, and then completed the year's flights by loading enough tankers to provide the propellant required for the year's missions. This manifesting mode turned out to be relatively inefficient because manifesting payloads together ordinarily resulted in volume-limited rather than mass-limited flights.

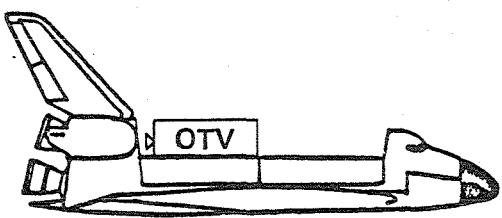
An improved space-based manifesting logic is diagrammed at the right. Shuttle center of gravity constraints will allow approximately 20,000 pounds of payload to be loaded in the front of the Shuttle payload bay if a reduced-capacity tanker is placed in the back of the payload bay. Approximately the same payload is



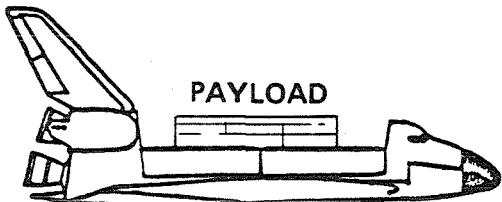
GROUND-BASED OTV



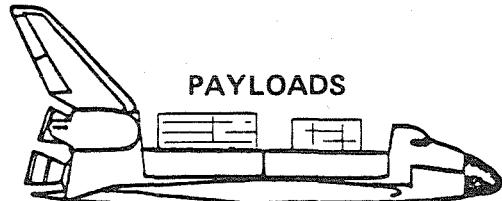
WHENEVER POSSIBLE



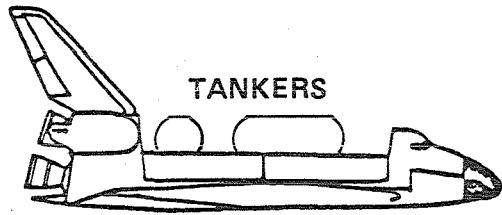
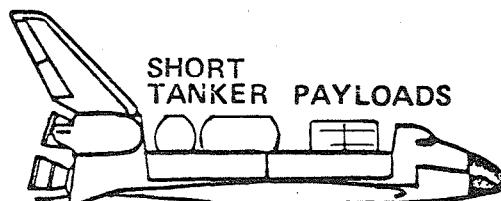
PAYLOAD



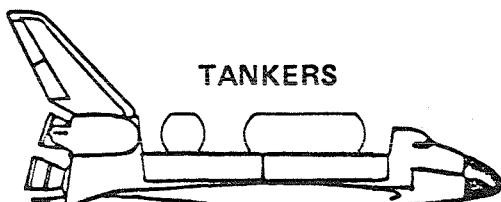
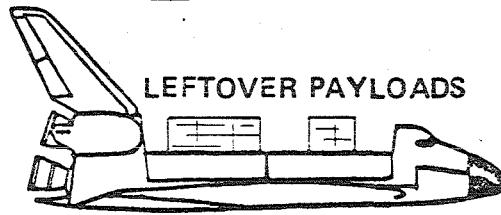
IF NECESSARY

SPACE-BASED
THE WRONG WAY

TANKERS

SPACE-BASED
THE RIGHT WAY

LEFTOVER PAYLOADS



IN EITHER INSTANCE, PROPELLANT
SCAVENGING FROM ET REDUCES
NUMBER OF SHUTTLE FLIGHTS
BY ABOUT 10%

Figure 14. Space Shuttle Manifesting Options

allowable whether the tanker is full or empty. Accordingly, a short tanker was designed with a propellant capacity of about 40,000 pounds (the tanker is illustrated in Figure 15). The manifesting logic manifests as many payloads with this short tanker as possible within the payload bay length and mass limits available. Those payloads that cannot be so manifested are then grouped together for additional Shuttle flights. Finally, any full-capacity tankers necessary to bring up the balance of the year's propellant are manifested.

In either of the space-based cases, scavenging propellant* from the ET can reduce the number of Shuttle flights by about 10%. Propellant scavenging increases the mass loading of either the short tanker or the full tanker. In addition, when payloads manifested together have space available in the back of the payload bay for a small receiver tank, additional propellant can be delivered on payload flights.

Five OTV design and basing options were analyzed in this study. These are compared in Figure 16 for the median mission model, for ETR launches only. A space transportation cost indicator was used: the number of Shuttle flights required plus the number of OTVs expended. Although neither the cost of an OTV nor the cost of a Shuttle flight are accurately known, it is presently thought that these costs are roughly comparable.

The comparison shows that the greatest leverage in reducing space transportation costs arises from the use of aerobraking in either the ground- or space-based case. The comparison also shows that space-basing offers an advantage of about 10% over ground-basing in the aerobraking case. Finally, the addition of ET scavenging adds about another 10%. The difference between the least effective and most effective OTV options is approximately a 40% reduction in the cost indicator.

*Rockwell has proposed a method of scavenging leftover ascent propellants from the external tank by delivering them to a receiving tank in the orbiter payload bay. The transfer operation occurs in a period of several minutes duration immediately following main engine cutoff (MECO). The external tank is then jettisoned for disposal in the usual way.

SOC-1473

32

D180-26785-1

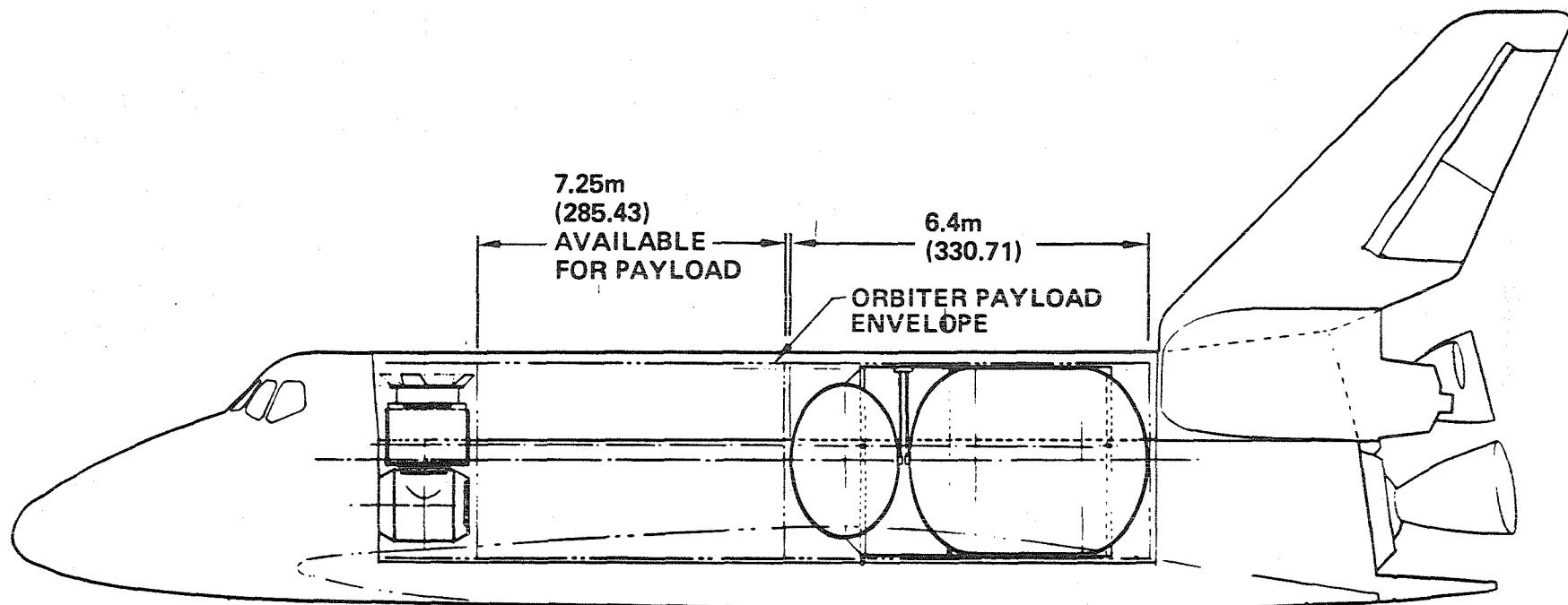


Figure 15. Mini-Tanker Concept

SPACE
TRANSPORTATION
COST INDICATOR:
SHUTTLE FLIGHTS
PLUS
OTV'S EXPENDED

33

D180-26785-1

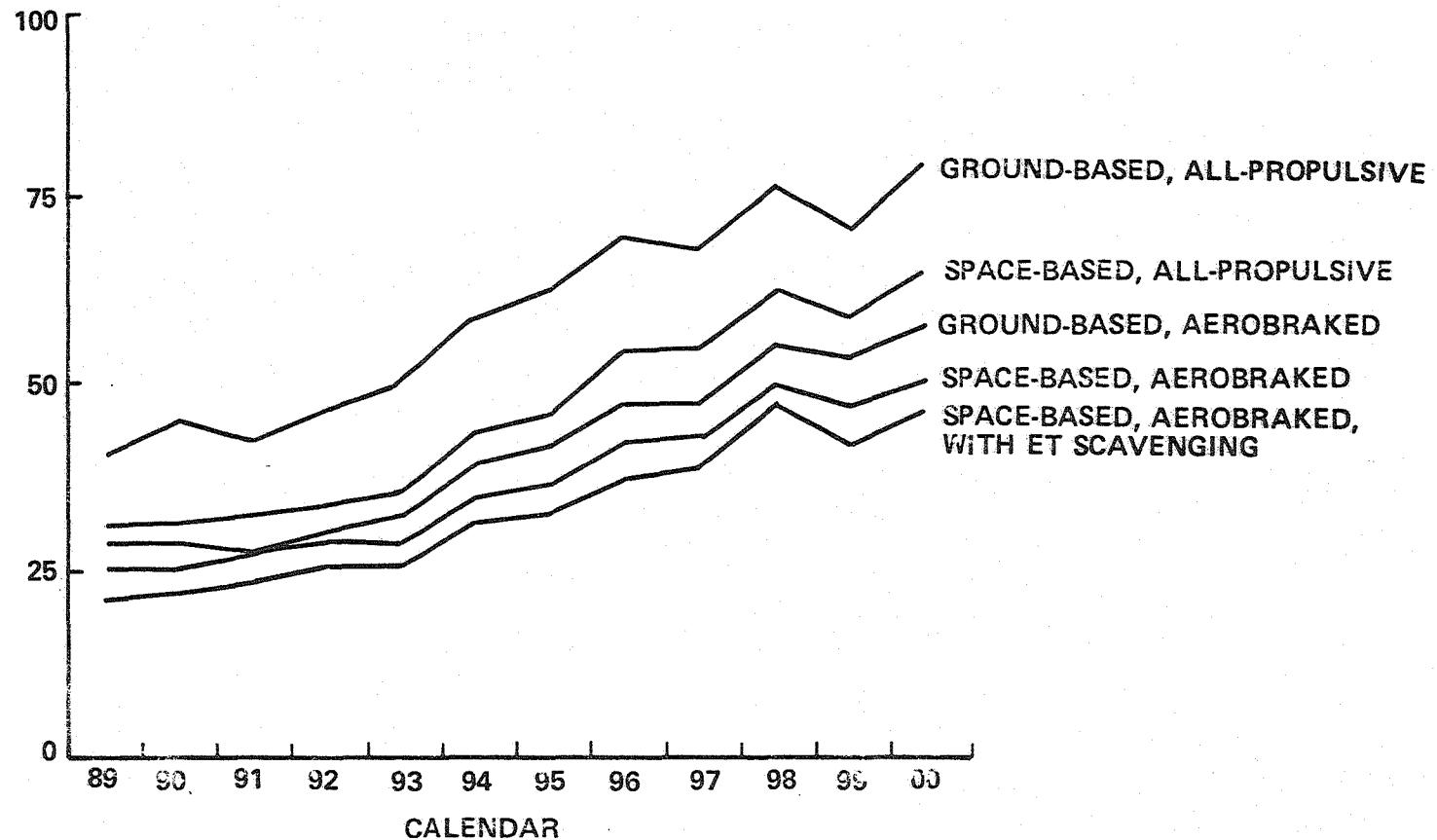


Figure 16. Comparison of OTV Operating Modes
Median Mission Model ETR Only

WTR launches were included to create a total space transportation demand forecast. The demand forecast for the three mission models is presented in Figure 17. This forecast assumes that space-based aerobraked OTVs are employed and that ET scavenging is implemented.

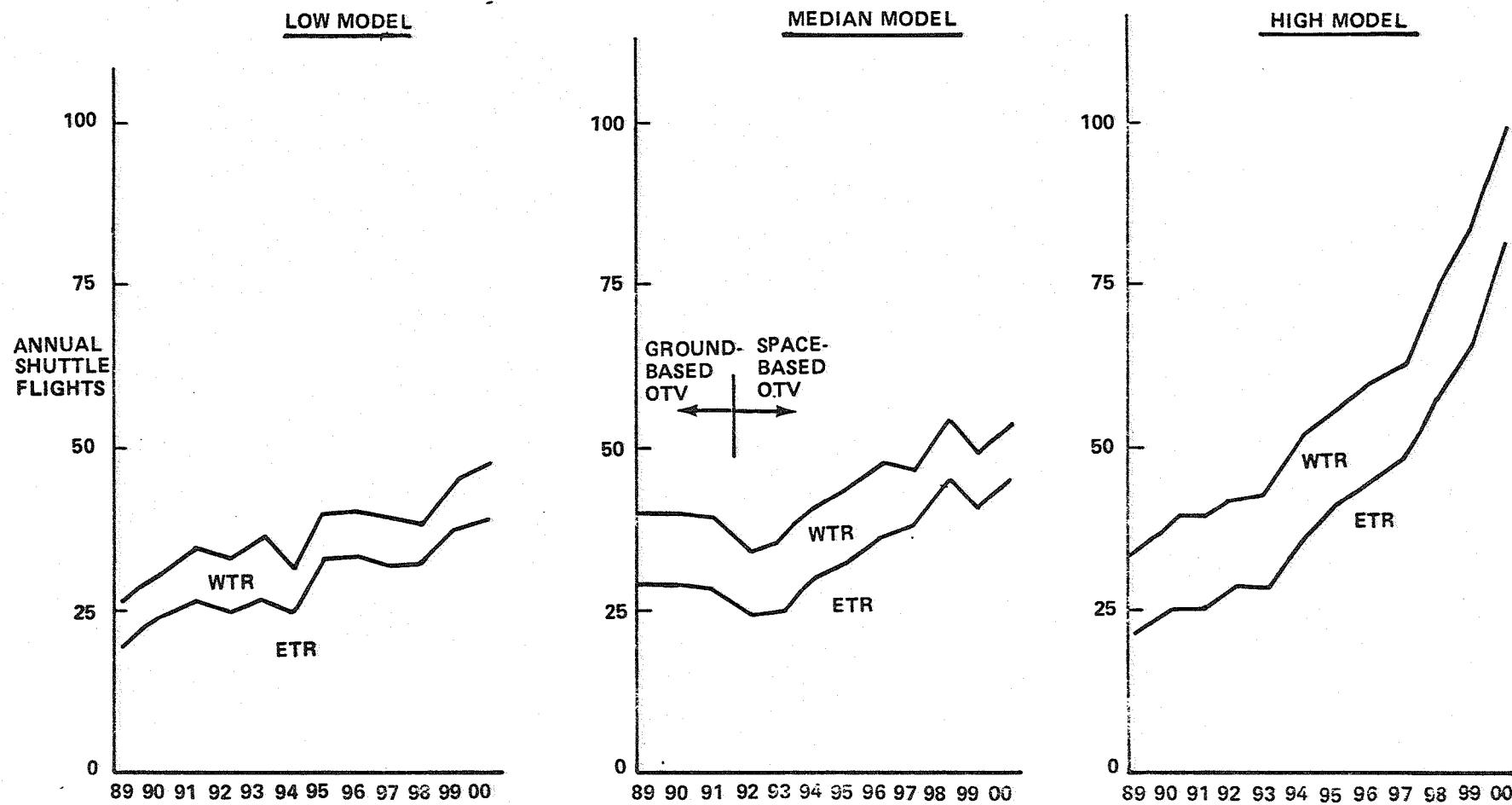
The total demand forecast for the low and median models is quite similar because the space transportation systems are used somewhat more effectively in the median models—there are more opportunities for payload grouping; on the average, the payloads are somewhat larger. Either of these models could be satisfied by a fleet of five orbiters, assuming a turnaround time of one month or less.

The high model reflects a rapid growth in space transportation demand approaching 100 Shuttle flights per year by the year 2000, a scenario in which extensive commercial and military investments in space activities would occur. Development of a second-generation space transportation system by the middle 1990s would be consistent with the high model scenario.

A SOC crew activities analysis operated on the results of the manifesting analysis. The crew activities analysis examines each Shuttle flight as manifested in sequence. Shuttle functions, OTV functions, construction functions, satellite servicing functions and onboard science and applications functions are analyzed. These are then summed up and printed for each flight, and for each year.

Consideration of whether to base OTVs in space or on the ground requires evaluation of the SOC involvement as well as evaluation of the transportation requirements. Shown on the left of Figure 18 are the annual Shuttle flights plus OTVs expended for three cases all with aerobraking of the OTV. Space-basing saves on the average about four equivalent Shuttle flights per year. However, it requires on the average about three-and-a-half extra SOC crew.

Based on a total operations cost estimate for SOC crew labor, the costs of space-basing for the crew labor are approximately \$1.67 billion over a 12-year mission



NOTE: THIS DEMAND FORECAST ASSUMES:

- 1) TRANSITION TO SPACE-BASED OTV IN 1992
- 2) ALL OTV's ARE AEROBRAKED
- 3) ET SCAVENGING IS IMPLEMENTED FOR SPACE-BASING

Figure 17. Total Space Transportation Demand Forecast (Aerobraked OTV)

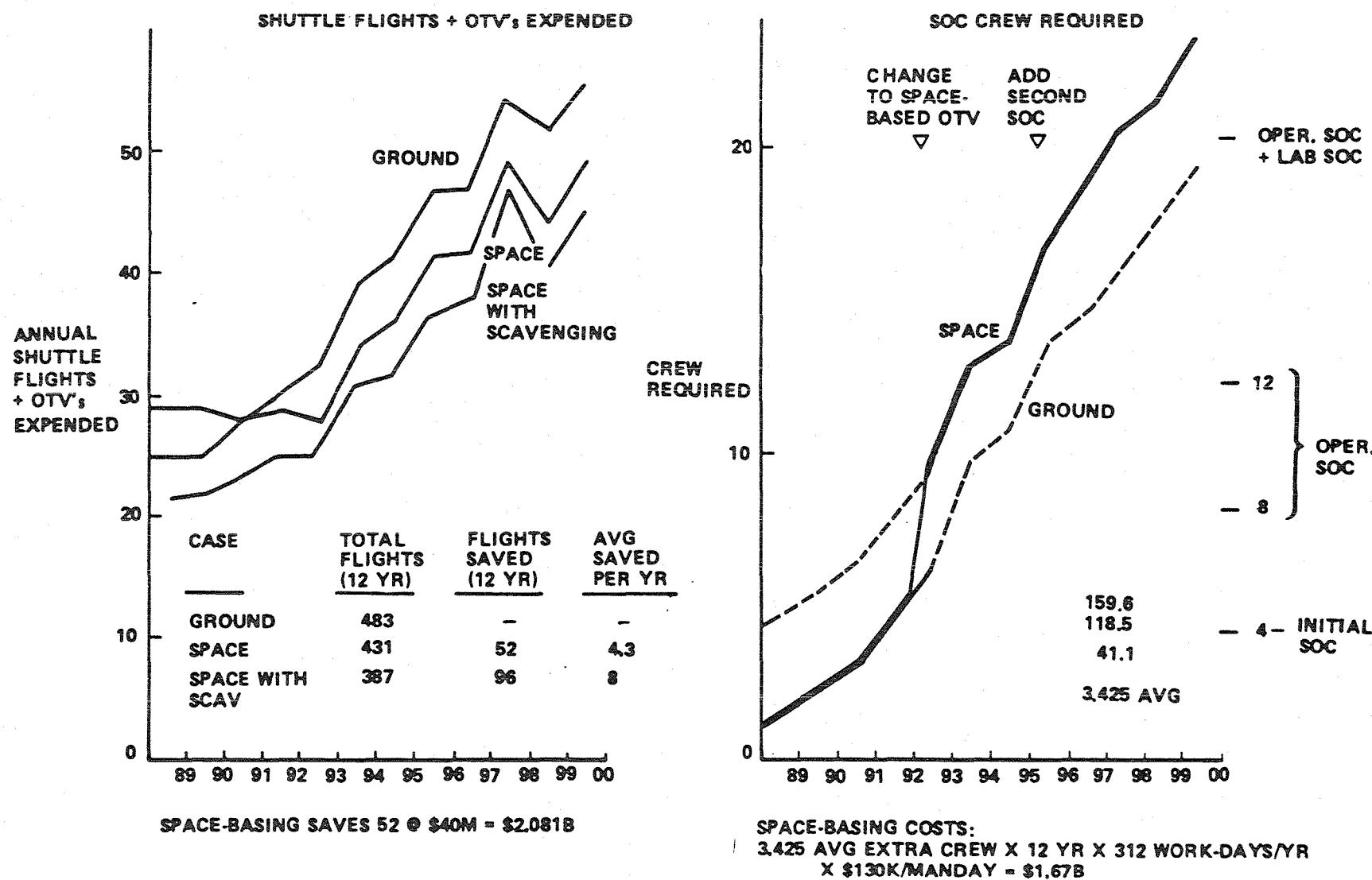


Figure 18. OTV Basing: Space vs Ground (Median Traffic Model)

model, and the savings are somewhat greater, approximately \$2 billion over the same period based on a \$40 million average Shuttle flight cost.

Several conclusions were drawn from this analysis.

First, the mission model is dominated by the commercial and defense sectors. This is an expected result inasmuch as economic growth and national security are important national priorities.

We found that OTV aerobraking is essential to reduce the demands on space transportation. It does not appear to make sense to develop an OTV without aerobraking. Finally, space-basing pays off as does external-tank scavenging. The OTV should be designed for space-basing even though it will probably be initially operated in a ground-based mode.

We found a definite need for the Space Operations Center. A manned space station pays off both for operations and for research and applications. SOC utility divides roughly evenly between the operations functions and on-board science and applications.

Because we project an increase in the SOC crew requirements with time, as illustrated on the right side of Figure 18, an evolutionary program is the best fit to mission needs. It would be logical to begin SOC operations with a ground-based OTV for the first two or three years. It will be most practical to ground-base the OTV until some operating experience with the vehicle is obtained. Further, the SOC crew will initially be, among other things, occupied with smoothing out station operations. It appears logical to begin with a four-man SOC and eventually grow to 12 or more people. Towards the end of the 1990s, it may be necessary to set up a separate station for research and applications missions.

3.0 SUMMARY OF SYSTEMS TRADE STUDIES AND DESIGN OPTIONS

This summary of trade studies and system and subsystem options describes the selection processes that created the present SOC reference and alternative system concepts. The presentation begins at the system level and progresses through major subsystem tradeoff studies.

3.1 SPACE OPERATIONS CENTER REFERENCE AND ALTERNATE CONFIGURATIONS

The reference configuration developed by the first phase of the study was presented earlier in Figure 1. This configuration represents a fully-operational system and is likely to be preceded by an initial system made up of fewer elements and supporting fewer people.

Development of the reference configuration was accomplished by tradeoff analyses on the fully-operational system and definition of an initial system as a potential evolutionary step. A growth configuration, shown in Figure 19, was also conceived. It was analyzed to ensure that the system concept was amenable to growth in facilities, equipment, and mission capability.

The second phase of the study made three significant changes to the reference configuration: (1) The berthing ports in the habitat modules were offset from the centerlines to (a) improve interior space utilization, and (b) improve visibility of outside activities from the command and control station; (2) the OTV hangar design was changed to simplify and streamline OTV operations; (3) the logistics module was redesigned to increase pressurized volume. This was necessary to accommodate science and applications equipment. The modified reference configuration is shown in Figure 20.

The Phase A Extension developed alternative module concepts aimed at greater system versatility and reduced early costs. These are described following a discussion of those configuration trades relevant to both the reference and alternative modular designs.

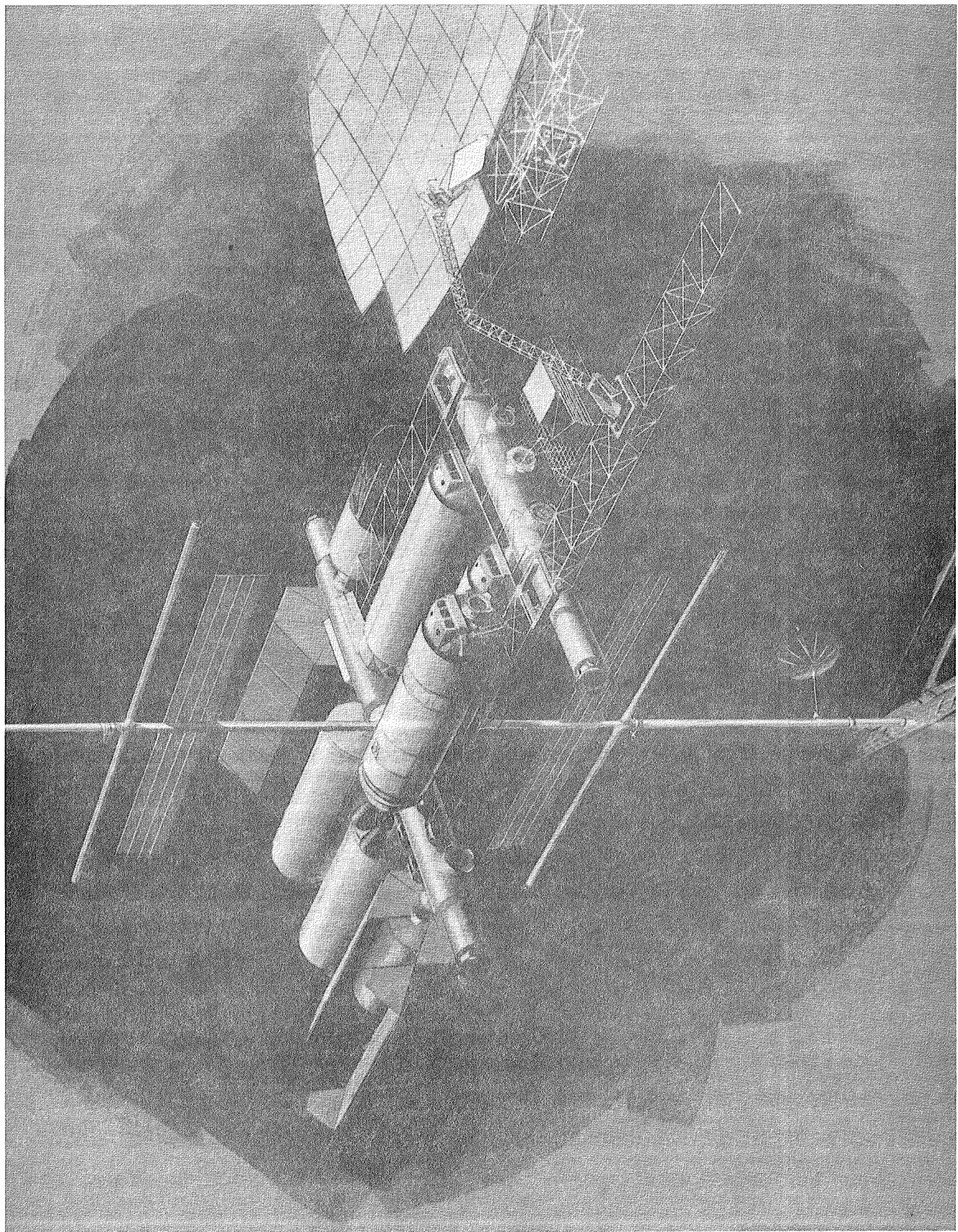


Figure 19. Growth SOC Configuration

SOC-1323

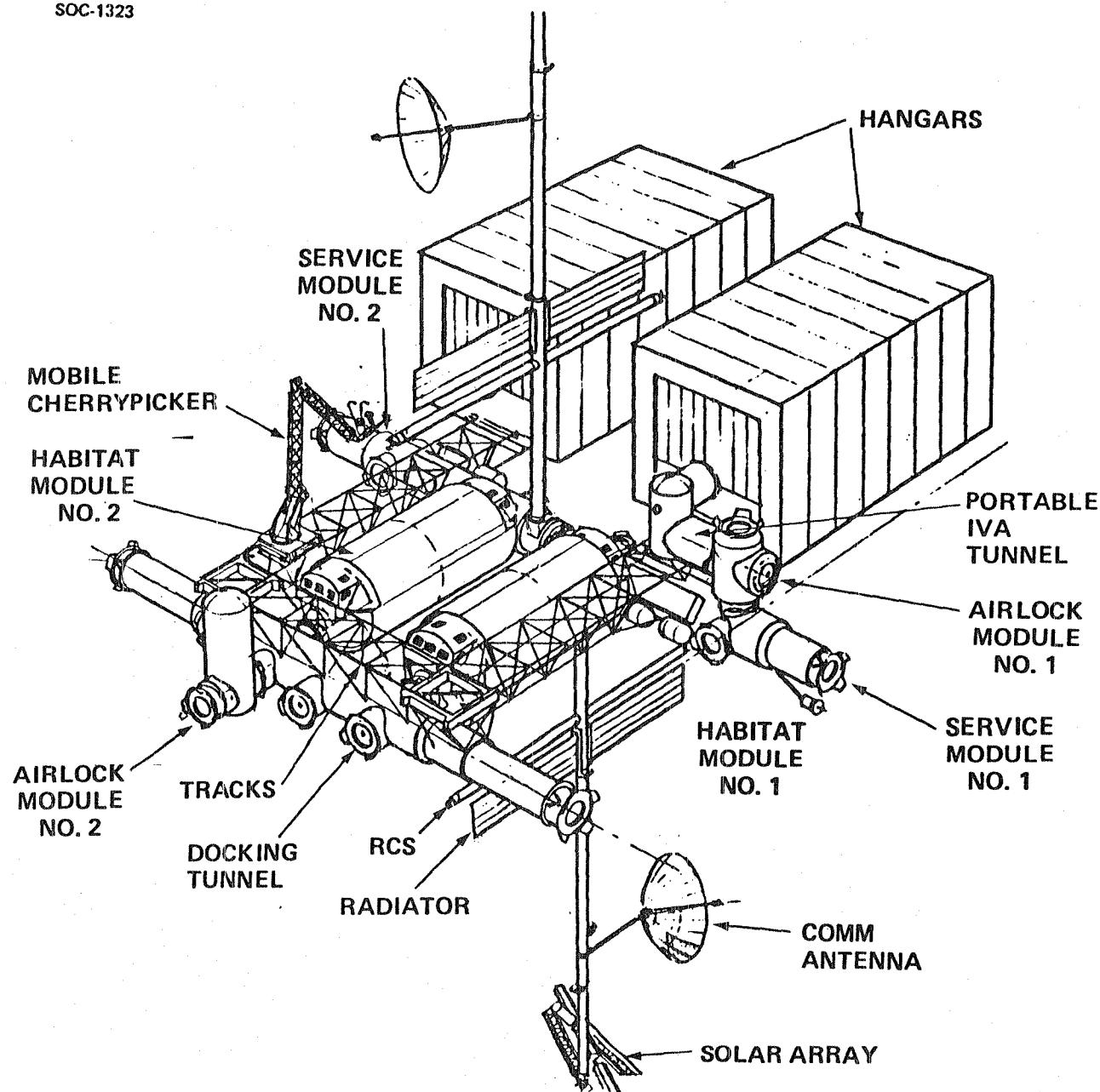


Figure 20. Operational SOC Configuration

The process by which the reference configuration was developed is summarized in Figure 21. The results of this configuration analysis apply to similar configurations employing alternative modules. The general arrangement of the system reflects four primary considerations: station orientation in its orbit, arrangement of the core modules, layout and size of the habitat and service modules, and location of facilities.

Flight Attitude

A spacecraft in a low Earth orbit may be Earth-oriented or inertially-fixed. For an Earth-oriented station, a particular part of the station is "down". The station maintains a constant attitude with respect to the Earth below it and consequently revolves once per orbit in inertial space. An inertially-oriented station maintains a fixed inertial attitude as Skylab did. The selection of orientation is dictated by mission and flight control considerations.

Inertial orientation can be important for an instrument platform. Skylab, for example, carried solar telescopes. Pointing these at the sun was simplified by the inertial orientation of the vehicle. Missions identified for the SOC do not require inertial orientation. Operations such as terminal rendezvous and docking or berthing of the Space Shuttle will be simplified by Earth-referenced orientation.

The applications science and technology missions most likely to be conducted at the SOC are life sciences and materials processing research. Additional candidate mission types include space testing, and, perhaps, tethered payloads. (The latter involves an instrument package deployed from the SOC on a tether up to one hundred or more kilometers long. This mission clearly requires Earth orientation.) The life science and materials research missions exhibit little preference. Certain materials research activities may require very low residual gravity fields. It will be important to locate these close to the center of gravity of the station, or on a free flyer. Some space testing missions will require instrument pointing; those compatible with SOC will generally involve relatively short periods of continuous instrument operation and modest pointing precision.

The flight control requirements for inertial, as compared to Earth, orientation are quite different. An inertial vehicle experiences cyclic torques due to gravity

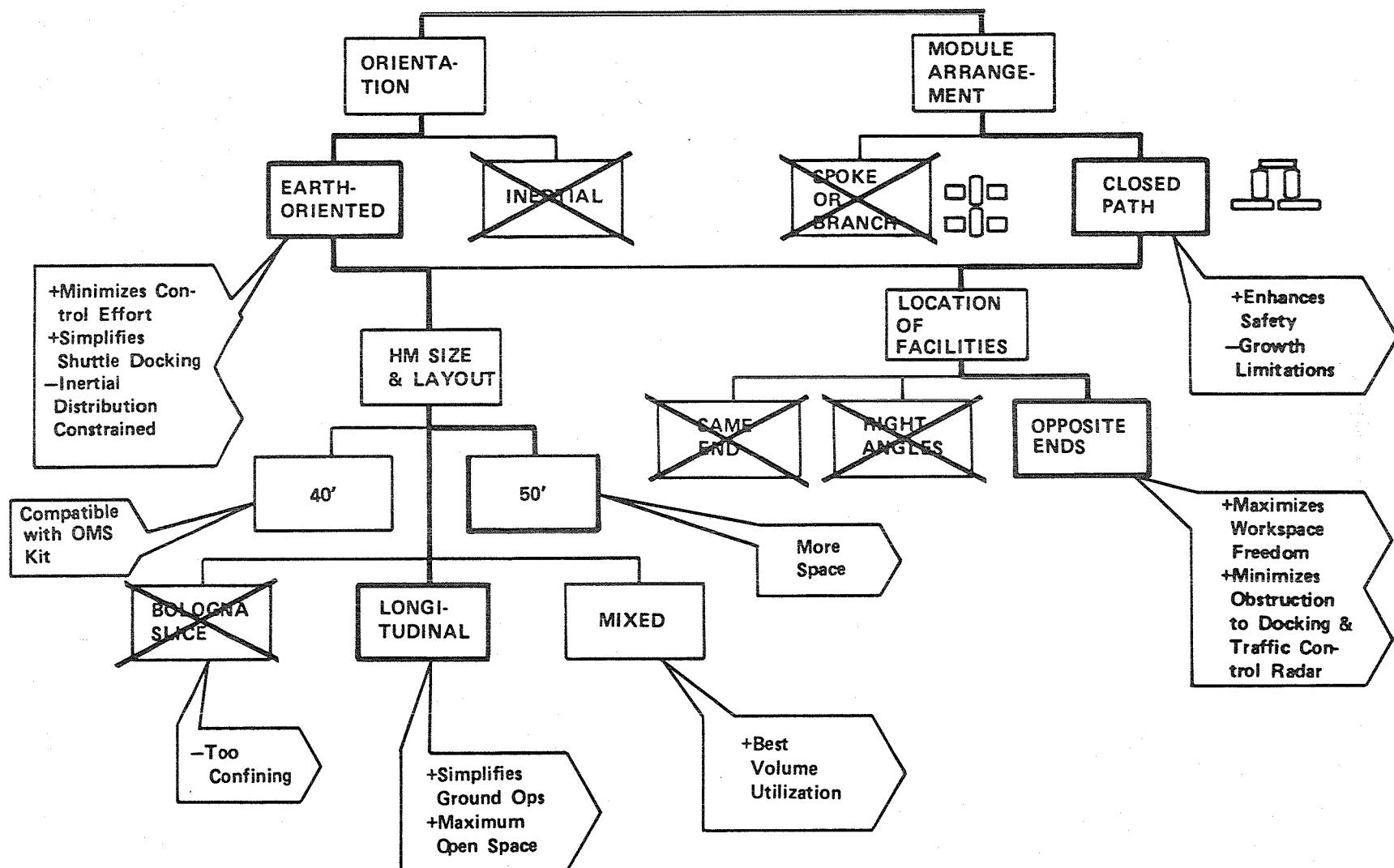


Figure 21. Summary of Options and Trades
SOC Configuration

gradients and air drag. These cyclic torques may be absorbed by a momentum exchange device such as a control moment gyro (CMG) without expenditure of reaction control propellant. An Earth-oriented vehicle experiences persistent gravity gradient and drag torques. A CMG offers no advantage over thrusters for absorbing these torques. The most practical way of minimizing propellant consumption for an Earth-oriented system is to arrange the configuration so that the desired attitude is stable with respect to gravity gradients, and to fly high enough that drag torques are small. Perturbations can be accommodated by allowing the flight attitude to shift with shifts in the principal axes of inertia.

Because of the operational nature of the SOC missions, the moments of inertia cannot be accurately predicted in a preliminary design phase - they will vary with the flight vehicles and spacecraft attached to the SOC for service, assembly, or checkout. If the SOC were to be inertially oriented, it would be necessary to include a large CMG capacity in the design with no real assurance that it would be adequate for the life of the system. Since no important inertial orientation requirement had been identified, it was decided to employ Earth orientation.

The SOC configuration general arrangement is compatible with the Earth-oriented flight mode. The moment of inertia about the axis of rotation must be the greatest. Distributing the core modules and principal facilities to lie in the orbit plane satisfies this requirement. Locating the facilities incurring the greatest mass variability at the top and bottom of the SOC ensures that these mass changes will not require large attitude changes to null gravity gradient torques. The necessary attitude changes are confined mainly to pitch rotations. Since the solar array drive is on the pitch axis, it can compensate for pitch rotations to keep the array fully illuminated.

Module Arrangement

Many modular manned space station concepts have employed a branched arrangement. This has been popular because it offers (at least in principle) unrestricted growth - more branches can always be added. The JSC SOC configuration was arranged like the reference configuration described above, with the pressurized modules connected by a closed path. This arrangement provides two routes of escape from each module, so that a crew member cannot be trapped in a module

by an intervening fire or accident. It does, however, restrict growth of the configuration. The module arrangement issue was reviewed with consideration of mission model forecasts. A need for more than twelve crew was not foreseen as likely; the present configuration can accommodate that number. The growth limitations of the reference configuration did not motivate a change to a concept with less inherent safety.

The modular nature of the SOC elements will enable creation of configurations including more than two habitat modules, should future mission needs develop for housing more than eight to twelve people. Presently it is believed that establishing additional stations, perhaps specialized to particular missions, is a more logical growth path than the creation of one large facility.

The various initial SOC configuration options do not fully comply with the safety rule requiring two shirtsleeve egress paths from each module. External airlocks provide an alternate EVA path between the habitat module and the service module. To provide an alternate path by development of a special tunnel does not appear warranted in view of the interim nature of the initial configurations.

Location of Facilities

The SOC configuration includes work facilities for spacecraft servicing and assembly (or construction) and for flight servicing of transportation vehicles. As the definition of the facilities proceeded, it was found that non-interference is the dominant consideration; this dictated location of the facilities at opposite ends of the SOC. The selected location, with transportation facilities toward Earth, also minimizes concern over loss of gravity gradient stability if massive or large payloads are located in a work area.

A very important consideration in the final definition of the facilities was the need to mate upper stages to platform-type spacecraft. The mating facility must not restrict the diameter of the payload to be mated. Accommodation of a platform payload is illustrated in Figure 22.

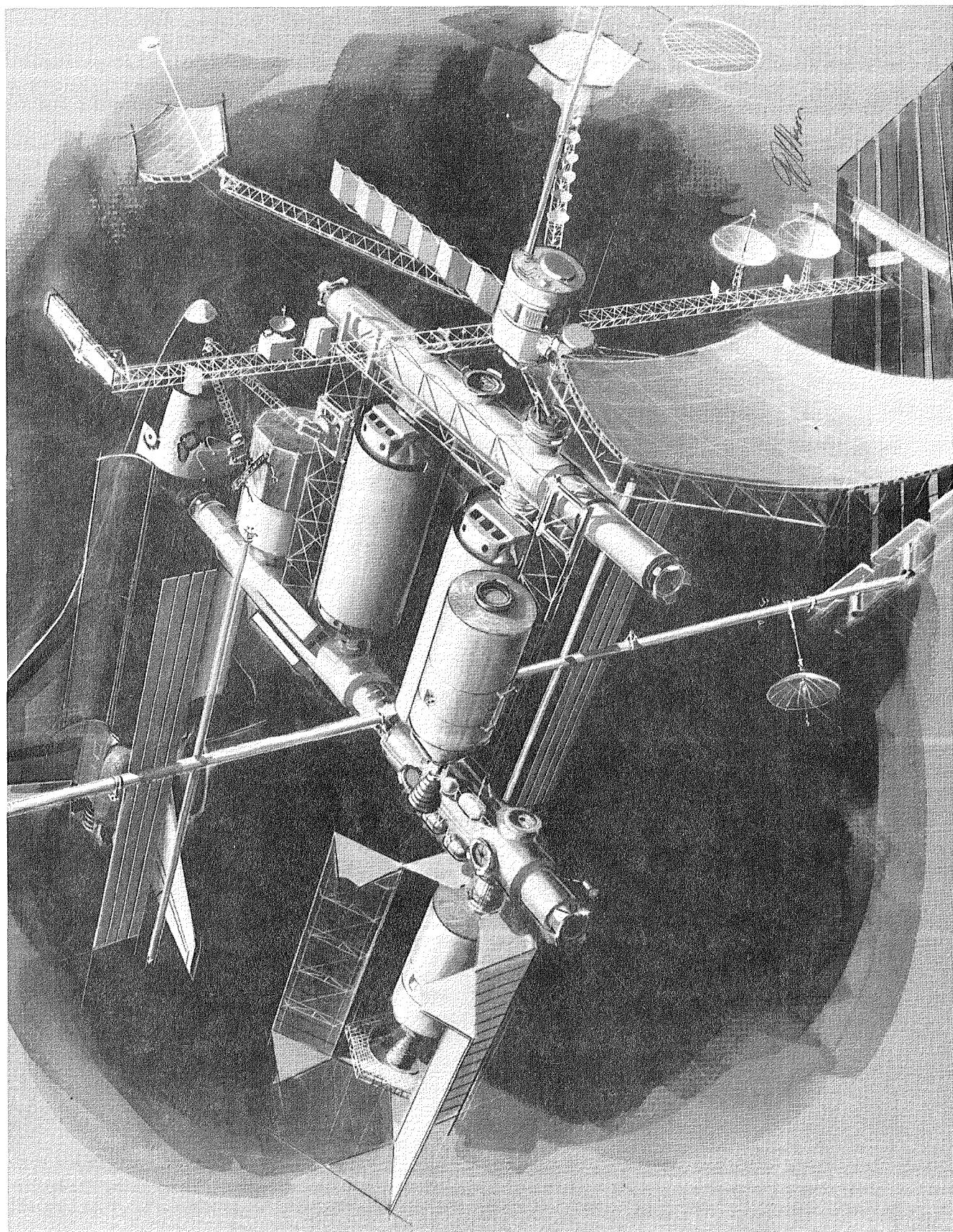


Figure 22. Operational SOC Configuration with Experimental Communications Platform Being Deployed

Alternative Configurations

The reference SOC design presented meets the system requirements contained in the SOC requirements document. However, a number of reasons have developed for considering alternative modular concepts. The principal ones are the following:

1. A number of alternative uses have been identified, including military applications, small geosynchronous stations, and stations designed primarily to support materials processing development and other science and applications operations.
2. If it were desired to place a manned station into a high inclination orbit, it would be necessary to reduce the major module weight in order to be compatible with reduced shuttle launch capability to high inclinations.
3. Simultaneous development of a Service Module, a Habitat Module, and a Logistics Module, as postulated for the reference program, leads to funding profile problems.
4. The mission needs analysis conducted as a part of this study identified a need for a Space Operations Center accommodating up to 12 people for the median traffic model by the year 2000. (A second station, devoted entirely to microgravity applications, with a crew of eight, may also needed by the year 2000.)
5. The same mission needs analysis indicated that an initial operational capability with a crew of four would suffice for a period of two to four years. This assumes that the orbit transfer vehicle would operate in a ground-based mode for this period of time. An incremental build-up approach is most compatible with these mission needs.
6. The mission needs analysis indicated a need for added interior space for science and applications missions.

The need to create a manned space station technology adaptable to diverse missions has led to a versatile modular approach to space station design. The keys

to this approach are (1) standard subsystems employing advanced technology to permit a long, useful life without obsolescence, and (2) modularization of the design at a level below that of complete station modules to allow creation of a variety of system configurations. Results thus far obtained confirm the benefits of the approach and indicate versatility to render a design as small as a single Shuttle-launched station and one large enough to support a crew of 12 to 20, all employing the same basic hardware set.

The key to this alternative design approach evolved from the original SOC service module. The service module includes the essential elements of a space station, including electrical power supply, consumables supply, and elements of the environmental control, thermal control, data management, and communications subsystems.

The first step in this evolution was equipping of the reference service module with emergency survival equipment, so that in an emergency, one service module could provide subsistence and life support for up to four crew members.

The next step in this evolution was to improve the habitability provisions in the service module so that it alone could serve as a modest space station with adequate, if austere, habitability provisions for normal operations for a period of one to four years. The improvement of accommodations necessitated increasing part of the service module diameter to improve its habitability.

This design approach has evolved a modified service module that is structurally common with the logistics module. The selected diameter allows masts, booms, and tanks to be packaged alongside the larger diameter section. This minimizes the number of joints in the masts. Packaging volume external to small-diameter sections is provided for large tanks and other external stores. The relative lengths of the large and small diameter sections of this modified Service Module are dictated by the volume requirements for external stores. A representative configuration is sketched in Figure 23. Figures 24 and 25 present 4-man and 12-man SOC configurations based on this modified service module.

Full-diameter habitat modules can be added at a later date. The versatile modular design approach allows the length and interior arrangements of these habitats to be tailored to the mission requirements. For the low inclination, low

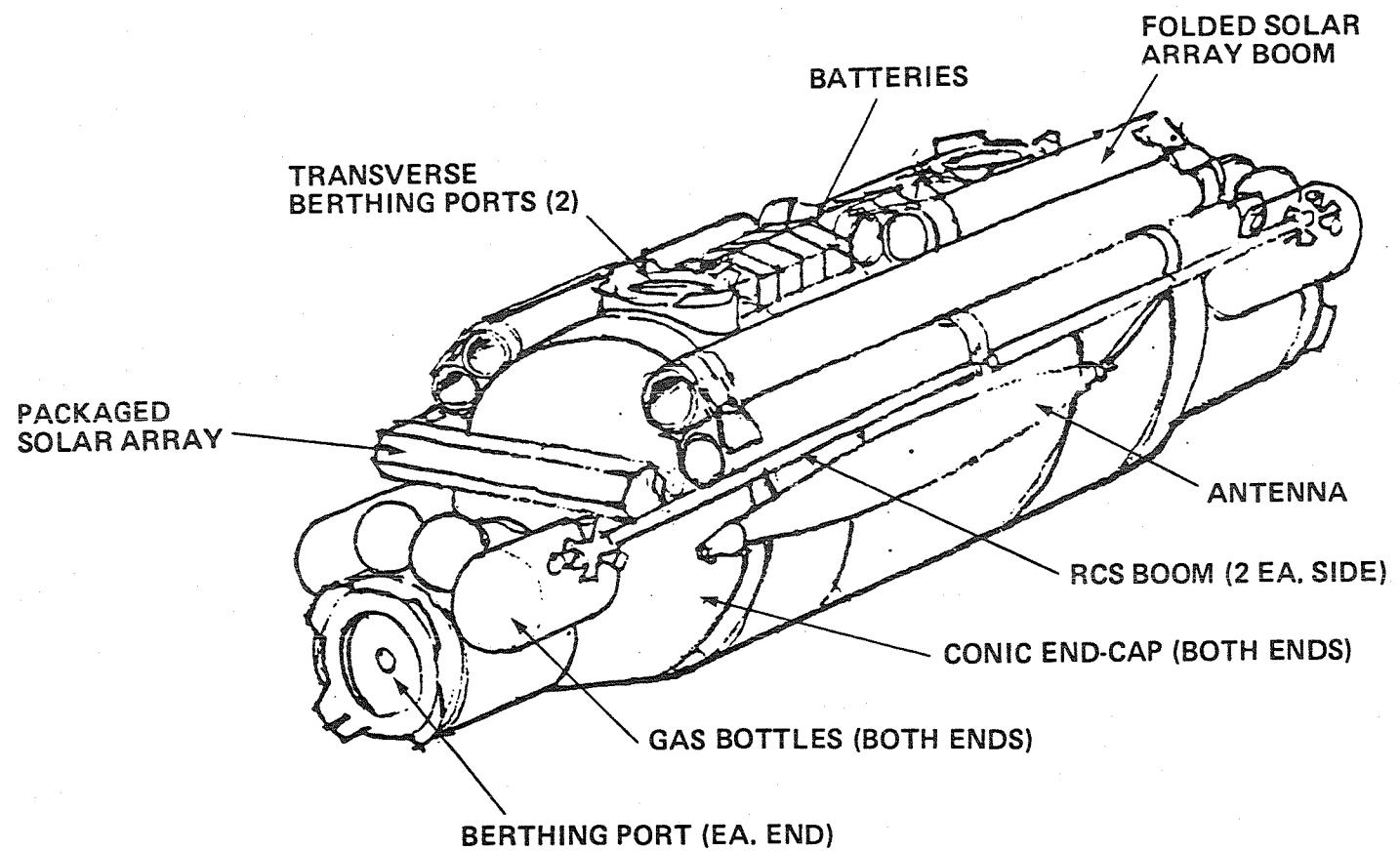


Figure 23. Modified Service Module

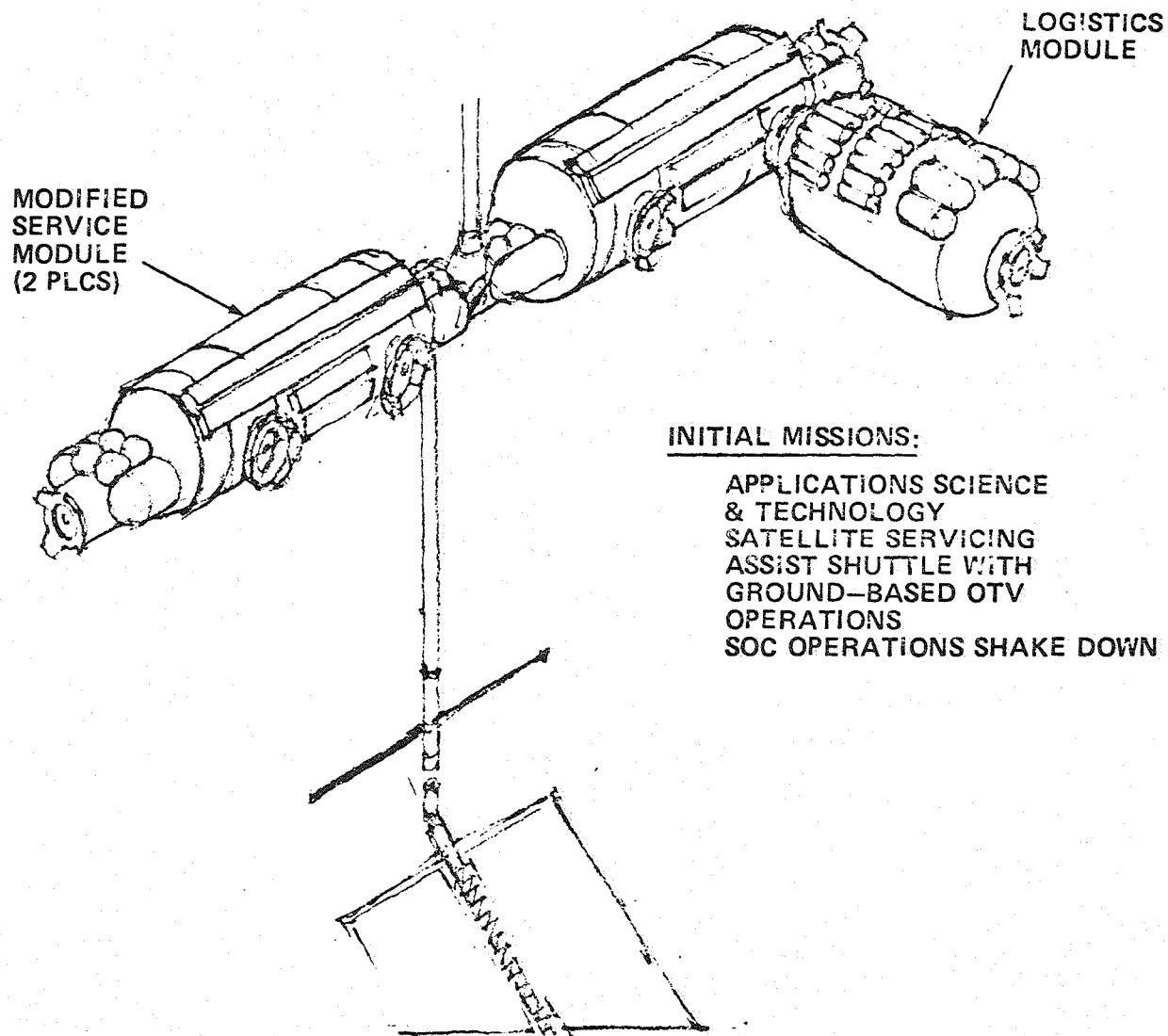


Figure 24. 4-Man SOC Concept

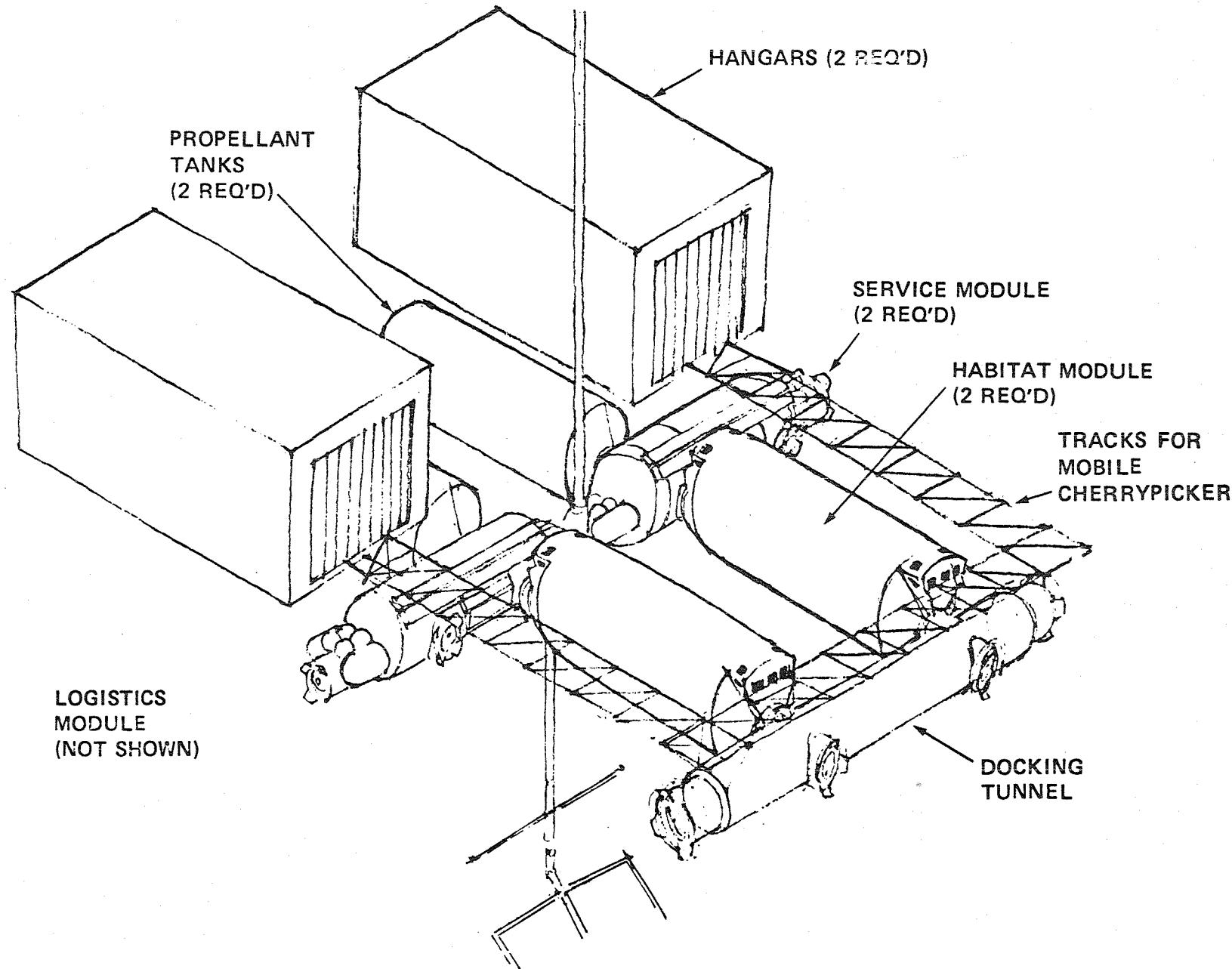


Figure 25. 12-Man SOC Concept

Earth orbit SOC designed for space operations service, a full-length (14-meter) habitat system can be used. Two such habitats will accommodate up to eight additional crew, for a total of 12. Overflow capacity within these modules is also available in the form of additional space for sleep stations for transient visitors not allocated private quarters.

Habitat Module Size and Layout

The habitat module configuration initially allowed space in the shuttle payload bay for an OMS kit; the habitat length was restricted to 12.2 meters (40 ft). Development of internal habitat arrangements indicated a need for additional space. Also, analysis of orbit altitude considerations indicated that the SOC orbit would be low enough that an OMS kit would not be needed. Consequently, the habitat module was lengthened to the degree permitted by mass and center-of-gravity considerations.

Initial layouts developed during the study employed a 14.9-meter (49 ft) length. Layouts were made for three alternative interior arrangements - lateral decks (dubbed the "bologna slice" concept), longitudinal decks, and a mixed-deck concept with both lateral and longitudinally-oriented areas. The "bologna-slice" arrangement was effective in its use of the available internal volume, but created an impression of confinement because of the small individual rooms and work spaces. The mixed-deck arrangement retains the effective volume use and includes a roomy galley, health maintenance, and recreation area. It has been retained as an option for further evaluation. The longitudinal deck arrangement, shown in Figure 26, was selected as a reference design. Concerns about ground handling, test, and simulation activities with the mixed-deck arrangement (it has different up-down orientations in different areas) led to its relegation to second preference. The longitudinal arrangement also facilitates a simple and effective cabin ventilation system.

As detailed mass and center-of-gravity estimates were developed, the 14.9-meter habitat module became marginal in both respects. The module must be launched in the shuttle with a 2-ton (4000-lb) docking module in the front of the payload bay. If the habitat module cg were exactly at the center of the module, the greatest length that could be accepted within shuttle cg limits is about 13.1

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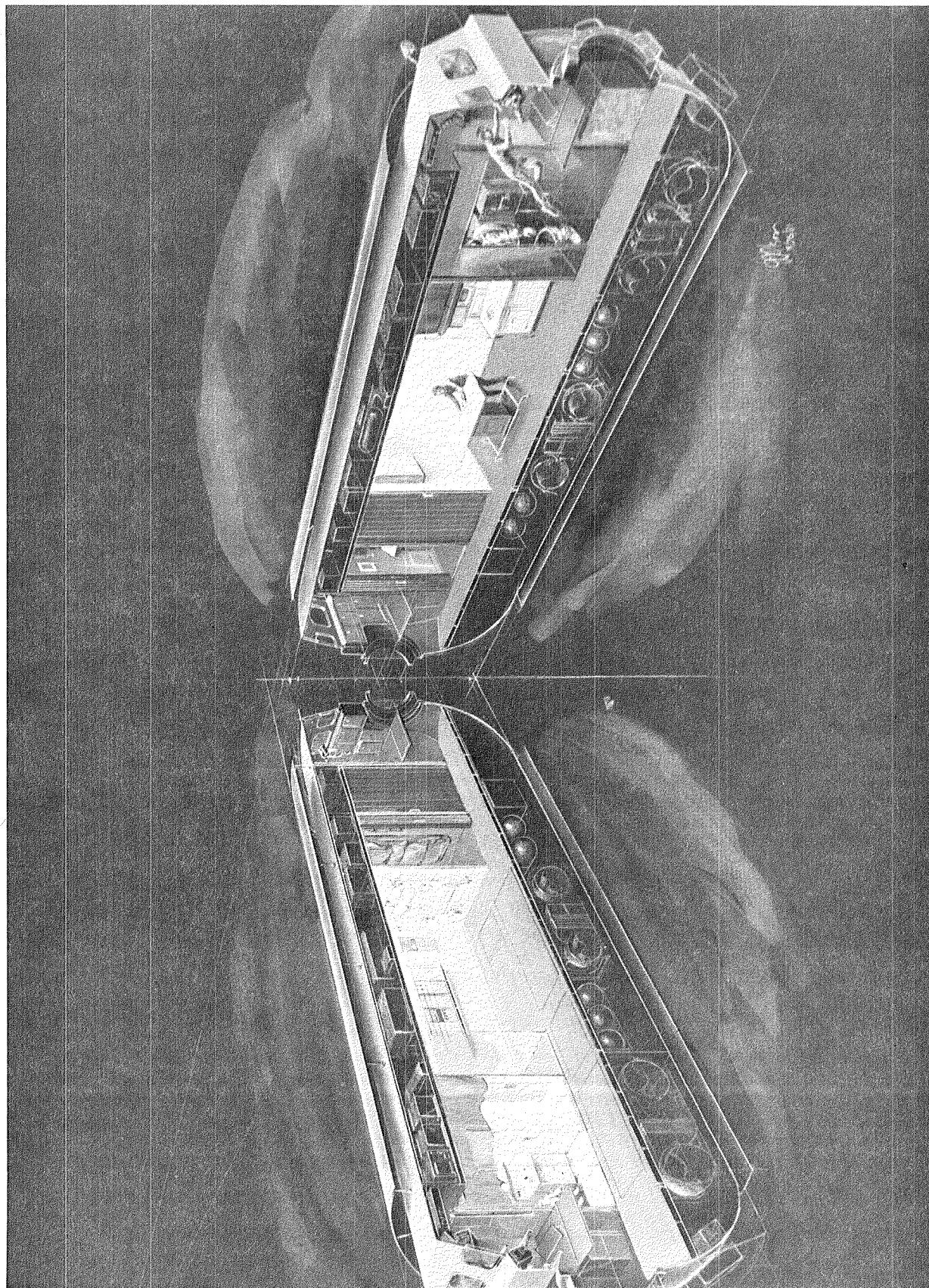


Figure 26. Habitat Module Interior Arrangement

meters (43 ft). Because the location of equipment within the module is not symmetric, however, the cg is offset about one meter (3 ft), and a 14-meter (46 ft) module may be accepted as shown in Figure 27. The present reference design permits length adjustments, as a part of further design development, to accommodate CG constraints.

The internal airlock included in the earlier habitat module configurations was deleted from the final configuration. This provides more usable volume in the somewhat shorter module as was available in the earlier 49 ft configuration. Removal of the airlock was partly motivated by mass considerations, but mainly because of the evolutionary buildup considerations discussed below.

3.2 SUBSYSTEMS TRADEOFFS AND ANALYSES

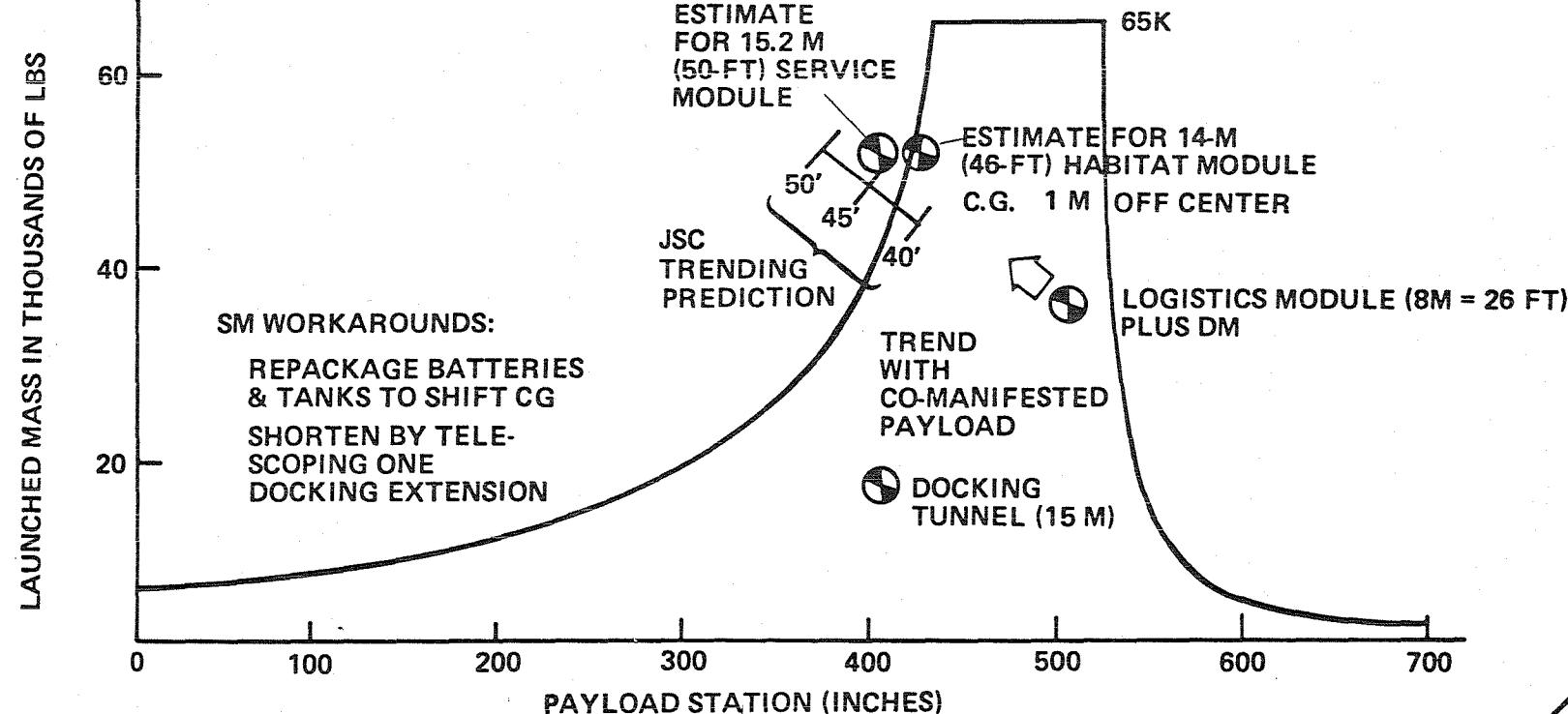
The tradeoffs and analyses of SOC subsystems considered each subsystem individually as well as the interrelationships among the subsystems, the software, and SOC operations. Software was considered as a part of the data management subsystem. The following discussion considers the individual subsystems first and then describes the principal results of the subsystems interrelationships analysis.

Environmental Control and Life Support

Analyses of the SOC environmental control and life support system (EC/LSS) were conducted by Hamilton Standard on a subcontract as a part of the SOC study. Their subcontract also included analysis of crew systems such as hygiene and galley equipment.

Closed Versus Open Loop—EC/LSS systems for prior U. S. spacecraft have been open-loop insofar as their handling of the waste products of human metabolism. CO_2 has been removed from the cabin atmosphere by LiOH cannisters. Waste water has been discharged overboard or retained in waste tanks. Solid wastes have been dried and stored. Fresh oxygen has been supplied from cryogenic storage. Fuel-cell-powered spacecraft such as Apollo and Shuttle have enjoyed an abundant fresh water supply as byproduct of electricity production; little motivation existed to recycle water on these vehicles.

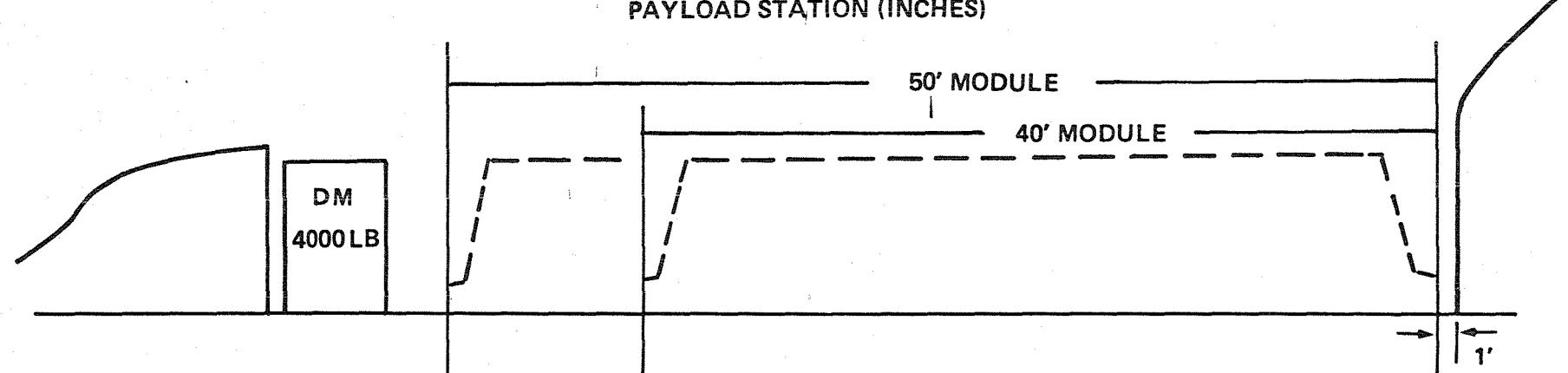
SOC-1110



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Figure 27 Module Weight and Length



Recycling water and reclaiming oxygen from CO₂ will be beneficial for a permanently-manned, solar-powered facility such as the SOC. The baseline SOC with eight crew requires the equivalent of two shuttle flights per year for resupply. If open-loop EC/LSS were used, the resupply requirement would more than double.

Closed-loop EC/LSS technology has been in development for several years; prototype equipment is now undergoing tests. Accordingly, the technical risk for adoption of a closed-loop system is manageable. With a payback time of less than five years for R&D investment in the closed-loop system, the choice of closed-loop for the reference system was clear.

Incremental steps in loop-closing have been identified that could reduce early program costs and technical risks. Most attractive among these is a plan that defers reclamation of oxygen from CO₂. In the initial system, only CO₂ removal might be implemented. Deferral of closed-loop production of potable water is also potentially attractive. These deferrals offer some reductions in initial program cost (as well as risk). It is important that these elements of the EC/LSS system would only be left out, not designed out. Provisions for their later installation would be retained in the initial flight system.

CO₂ Removal—Two options were considered for removal of CO₂ from the cabin atmosphere. An electrochemical system, employing a fuel cell principle, has been under development for several years, as has the use of a regenerable solid amine bed.

The electrochemical system utilizes hydrogen in a reaction involving OH and CO₃ ions, to absorb CO₂ from the cabin air stream and re-emit it into the hydrogen stream on the other side of the cell. The hydrogen-CO₂ stream then goes to a Sabatier reactor where the oxygen is regenerated.

The solid amine system utilizes a solid amine bed through which the cabin air is circulated. The solid amine particles are retained in a cannister by filters. The solid amine material preferentially absorbs CO₂. When the bed is saturated with CO₂, cabin air flow is discontinued and steam is introduced to the bed. The hot steam drives the CO₂ out of the bed; CO₂ is routed to the Sabatier reactor where

it is reduced by hydrogen from the water electrolysis unit. When the bed is desorbed, it is then returned to CO₂ removal service.

The solid amine system consumes electric power for steam generation when being desorbed. When absorbing CO₂, it consumes only fan power, but the desorption steam comes out of the bed as water vapor. This places an added load on the humidity control and thermal control systems. The electrochemical reactor actually generates a small amount of electric power through its consumption of hydrogen. The hydrogen must be generated by electrolysis, however, so in net terms, the electrochemical system is the greater power consumer. It also is more dependent on operation of other systems than solid amine requiring, for example, electrolysis hydrogen flow. (The solid amine system requires hydrogen flow to the Sabatier reactor to recycle CO₂, but can remove it without hydrogen.)

The solid amine system was selected in view of its lesser mass and power requirements and simpler interrelationships with other EC/LSS system elements.

Equipment Cooling—The shuttle uses cabin air as the primary means of cooling electronic equipment. This approach was considered for SOC, but rejected in favor of use of cold plates so that equipment would be operable with loss of cabin pressure. If, for example, a habitat module were temporarily evacuated, its data management and communications equipment should still be operable. Further, use of cold plates minimizes concern for adequacy of equipment cooling if the selected cabin pressure should be reduced after cooling parameters are finalized.

Cabin Ventilation—Cabin ventilation concepts evolved with habitat module internal arrangement concepts. The selected ceiling-to-floor approach is most compatible with the longitudinal deck arrangement, and presents less concern for debris movement through the cabin than does an end-to-end concept. It also allows the under-floor and over-ceiling volumes to be used as plenums and minimizes air ducting. Circulation through the closed path established by the module interconnections concept was rejected early. It is not compatible with safety requirements for emergency operations with hatches closed.

Nitrogen Supply—Nitrogen is to be derived from hydrazine to avoid the problems attendant to either liquid or gas nitrogen storage. Hydrazine is over 90% nitrogen by weight; it can be decomposed in a chemical reactor to release the nitrogen.

The hydrazine supply is common with that for orbit makeup and attitude control propulsion. If another propellant is selected for SOC as discussed below, the nitrogen supply question should be reopened; use of a shuttle cryogenic oxygen tank, in the logistics module, for nitrogen supply, would be attractive.

EC/LSS Equipment Location—Some of the earlier space station studies have employed centralized EC/LSS, i.e. one module devoted entirely to EC/LSS equipment, with air and water circulation to other modules as needed. For SOC, this concept was rejected in favor of a distributed system because the latter is more compatible with the evolutionary buildup approach and allows each module to be self-sufficient in life support under emergency conditions.

Cabin Pressure—The selection of cabin pressure included effects of fire safety, metabolic oxygen requirements, oxygen toxicity, oxygen pre-breathe requirements for EVA (to prevent nitrogen embolism or "bends"), suit design, and other equipment compatibility. The recommended SOC cabin pressure is in the range of 11 to 12 psia, with an associated EVA suit pressure of about 5.5 psia. If a higher-pressure (8 psia) suit is developed, SOC cabin pressure should be set at one atmosphere (14.7 psia). SOC design flexibility should be maintained until the suit pressure issue is settled.

Electrical Power

Electrical power options include fuel cells and solar array-battery systems. Because the SOC nominal electrical loads total about 50 kilowatts, a fuel-cell system would impose a burden of roughly 40,000 kg resupply every 90 days. Consequently, solar power is a clear choice.

Solar Array—The lightweight, flexible deployable solar array technology presently in development provides great advantages to SOC and was a clear choice in mass and packaging volume.

Batteries—The SOC will operate in a low Earth orbit with an orbit repetition of about fifteen orbits per day. Each orbit will include a shadow period of up to 36 minutes. A battery system is necessary to serve the SOC loads during shadow periods; over a ten-year SOC life the batteries will experience about 60,000 charge-discharge cycles.

The present reference electrical power system for the Space Operations Center uses solar arrays as a primary power source, and nickel-hydrogen batteries for storage of electricity to provide power during the part of each orbit shadowed by the Earth. This type of system, coupled with a closed-cycle environmental control and life support system, reduces consumables resupply to the point that it is dominated by food requirements. Resupply then represents only a minor burden on the space transportation system.

Nickel-hydrogen batteries were selected because of their relatively good tolerance to repeated charge-discharge cycles. Comparison of nickel-hydrogen batteries with nickel-cadmium for this application indicated roughly a 50% savings from use of the nickel-hydrogen technology. The packaging volume of nickel-hydrogen batteries, however, presents a problem to design of the service module. Further, the development of a nickel-hydrogen system capable of handling the 50-kW load of the SOC presents a significant technology challenge.

A high-performance "battery" can also be provided by operating water electrolysis units to store energy and fuel cells to deliver energy. Very preliminary calculations indicate this to be attractive as an energy storage system for SOC, if certain technology challenges can be met. This approach presents three advantages as an electrical power system:

1. Using shuttle orbiter fuel cells (each service module would need about four of these), the mass of the energy storage system will be on the order of one-third that of nickel-hydrogen batteries.

2. The volume, assuming that the reactants are stored as gas, will be smaller.
3. If cryogenic propellants for upper stage use are stored aboard the SOC, the quantity normally available would permit one to two months' operation under emergency conditions without dependence on solar arrays.

Five additional advantages accrue from integration with other SOC subsystems:

1. Fuel cells can reject heat at higher temperatures than batteries. The use of fuel cells would permit connecting service module thermal loads in series that are now in parallel. The radiator inlet temperature could thus be raised an estimated 20 to 25 degrees C.
2. If small gas-gas hydrogen/oxygen thrusters were operated from the gas storage supply for orbit makeup, their consumption would be only about 2% of the throughput capacity of the system. Thus the orbit makeup propellant could be derived from water delivered on resupply flights. The orbit makeup propulsion would be increased to about 375 seconds.
3. Hydrazine can be eliminated from the SOC system, thus avoiding its hazards on orbit as well as in the handling of the resupply module.
4. Surplus oxygen will be available for cabin leakage makeup.
5. New hardware development requirements are reduced.

Three issues need further analysis:

1. The present lifetime of the shuttle fuel cells would lead to frequent replacement. Improvements now in progress, however, are expected to extend the lifetime of the fuel cells to 10,000 hours or better.
2. The rapidity with which the fuel cell load can be changed, and the minimum output that can be permitted on the sunlit side of the orbit, need further assessment.

3. The efficiency of the fuel-cell electrolyzer system is expected to be less than that of a conventional battery. This means that a larger solar array will be needed.

Distribution—An array voltage of 200 was selected to reduce the mass of cabling from the array to the power processing equipment. This voltage is low enough to avoid the plasma loss associated with high-voltage arrays. Power electronics to handle a 200 volt array will need development. 28-volt DC and 110-volt, 400-Hz, 3-phase AC busses were selected to maximize equipment compatibility. Motor loads, for example, prefer AC power.

Propulsion

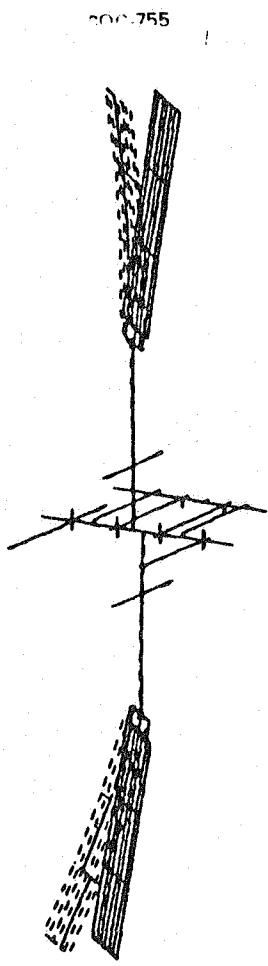
The SOC requires propulsion to maintain its orbit altitude and to control attitude. The propulsion configuration was selected to allow the orbit makeup thrust to also serve for attitude control; this configuration decision fits in with the Earth-oriented flight attitude. Location of the thrusters on booms may be seen in the configuration illustration, Figure 1.

The thrust level required for orbit makeup and attitude control is about 50 Newtons (10 to 12 pounds) on each boom. The thrust level required for controlled deorbit of the SOC is about 4000 Newtons (1000 pounds) on each boom. The controlled-deorbit requirement is subject to change; this would eliminate the requirement for the high thrust level.

The principal propulsion issue was propellant selection. A wide range of possibilities exists. Hydrazine was selected as a reference, with gas-gas O₂-H₂ as an alternate. Use of electrically-heated thrusters to augment the hydrazine Isp needs further evaluation.

Flight Control and Structural Dynamics

The lowest frequency structural modes solar array modes. Figure 28 illustrates the first solar array structural mode at 0.04 Hz. One configuration, with a large construction project attached, exhibited a first mode of about 0.008 Hz. This underlines the need for adaptive control - the dynamics of the SOC throughout its



*Figure 28. SOC Modes – Configuration 1
Mode 7 Freq. 0.042255*

lifetime in orbit cannot be predicted at the time the control system is designed. Further, the SOC dynamic modes are closely-spaced as illustrated in Figure 29. Another source of dynamics concern, not evaluated, is the presence of a cryogenic propellant storage facility in the "growth" SOC configuration. The normal condition of this storage facility will be partially loaded. Zero-g slosh damping must be included in the control system design.

Control-moment gyros (CMG's) were not seen as useful for primary attitude control of the SOC as discussed earlier. Initial dynamic simulations have revealed low-level cyclic torques that can profitably be controlled by CMG's, however, and their use is recommended. Further analysis is needed to establish sizing.

Communications and Tracking

The SOC must communicate with many space systems. This will require a relatively complex communications system with numerous antennas. The selected antenna types and locations are shown in Figure 30. The high-gain antennas are located on the solar array booms to allow communication with geosynchronous relay satellites. The traffic control radar antennas are located near the service module docking ports to minimize blockage.

A primary communications issue is RFI in the time period of SOC operations. NASA S-band is already over crowded and presents problems. K-band is becoming crowded with the rapid growth of space communications using this band; the SOC will frequently pass through comsat beams using these bands. Further, the planned TDRSS systems are expected to be nearly saturated with other users by 1990.

Because of these concerns, millimeter-wave communications capability has been included in the SOC baseline. Preferred frequencies are 65 GHz and 114 GHz. Even if relay satellites with millimeter-wave capability are not in place when the SOC initially becomes operational, this equipment should be included in the SOC in view of the difficulty of retrofitting in space.

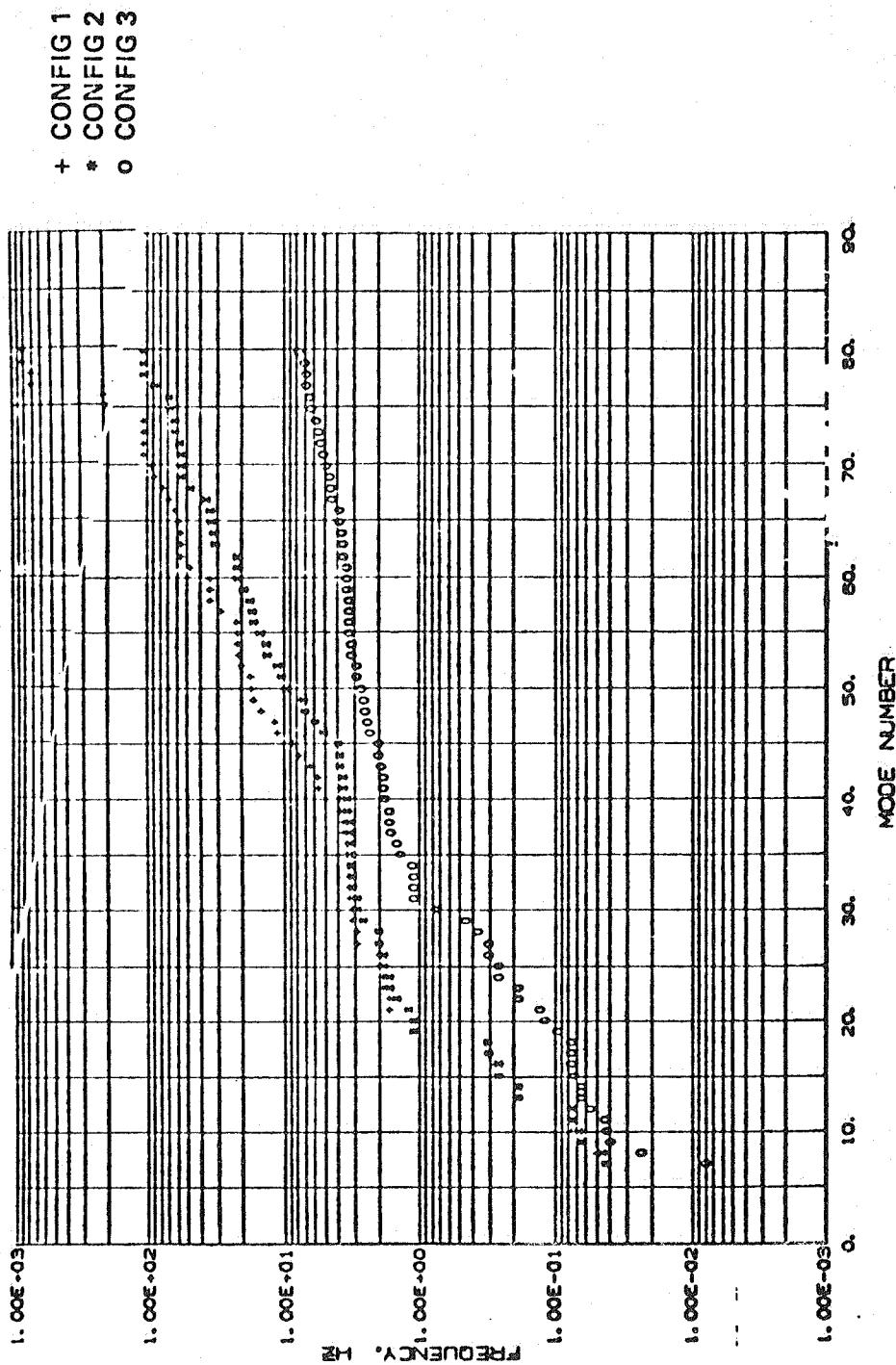


Figure 29. SOC Modal Frequencies

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COMMUNICATION LINK	TYPE R/T	FREQ. BAND	DATA	ENCRYPTION	CODING	FORMAT	MAX RANGE (KM)
SOC-TO-RELAY (RETURN)	NASA STD TDRSS	KU-BAND	TV: 25-50 MBPS DATA: < 1 MBPS VOICE: 16 KBPS	NO DES DES	NO VITERBI	DG-2 I CHANNEL Q CHANNEL	
RELAY-TO-SOC (FORWARD)	NASA STD TDRSS	KU-BAND	TV(OPT): 22 MBPS DATA(CMD): < 1 MBPS VOICE: 16 KBPS PN: ~ 20 MCPS	NO DES DES NO	NO MASSEY MASSEY NO	I CHANNEL Q CHANNEL	48,000
SOC-TO-OTV (FORWARD)	NASA STD TDRSS	S-BAND	DATA/CMD: 16 KBPS VOICE(MOTV): 16 KBPS PN: ~ 3 MCPS	TBD TBD NO	NO NO NO	I CHANNEL Q CHANNEL	≤ 600
OTV-TO-SOC (RETURN)	NASA STD TDRSS	S-BAND	DATA/TLM: 64 KBPS VOICE(MOTV): 16 KBPS PN: ~ 3 MCPS	TBD TBD NO	NO NO NO	DG-1 MODE 1 MODE 2 WITH ABOVE	
SOC-TO-ORBITER (FORWARD)	NASA STD STDN	S-BAND	DATA/CMD: 2 KBPS VOICE: 16 KBPS RANGETONES: 40Hz-500KHz	NO	NO	16 KHz SC 70 KHz SC SIDETONES	≤ 600
ORBITER-TO-SOC (RETURN)	NASA STD STDN	S-BAND	DATA/TLM: 64 KBPS VOICE: 16 KBPS RANGETONES: 40Hz-500KHz	NO	NO	SGLS SC 1.024 MHz SGLS SC 1.7 MHz SIDETONES	

DES-DATA ENCRYPTION STANDARD

Figure 30. Communications and Tracking Summary

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COMMUNICATION LINK	TYPE R/T	FREQ. BAND	DATA	ENCRYPTION	CODING	FORMAT	MAX RANGE (KM)
SOC-TO-GSTDN (RETURN)	NASA STD STDN	S-BAND	DATA/TLM: 64 KBPS VOICE: 16 KBPS RANGETONES: 40Hz-500KHz	DES DES NO	VITERB: VITERB: NO	SGLS SC 1.024 MHz SGLS SC 1.7 MHz SIDETONES	
GSTDN-TO-SOC (FORWARD)	NASA STD STDN	S-BAND	DATA/CMD: 4 KBPS VOICE: 32 KBPS RANGETONES: 1.7 MHz	DES DES NO	NO NO NO	BASEBAND 1.7 MHz SC	2800
SOC-TO-SCF	NO REQUIREMENT						
SCF-TO-SOC	NO REQUIREMENT						
EVA		UHF	VOICE: (FULL DUPLEX) ALSO VOICE BW DATA	NO	NO	AM	≤ 1.8
GPS-TO-SOC	GPS	L-BAND	NAV DATA			GPS	18,500
TRAFFIC CONTROL RADAR		MM	MULTIPLE TARGET DATA	N/A	N/A	PULSE CODED	≤ 8 2000 GOAL
SOC-TO/FROM FUTURE SATELLITE	NASA STD TDRSS	S-BAND	TBD				

DES-DATA ENCRYPTION STANDARD

Figure Communications and Tracking Summary (Cont'd)

Software and Data Management

The design of the SOC data management system involves several unique considerations that led to the selection of a distributed-architecture system for SOC:

- o The service module(s) must fly autonomously during the buildup phase
 - Off-nominal flight attitudes
 - Special flight control laws
 - Ground and shuttle command and control
- o The system will be used for 10 years or more in a changing operational environment
- o Presence of the crew requires interactive operation but permits:
 - Maintenance and repair
 - Hot/cold restarts
 - Override
 - Exchange of mass storage media
- o The crew-software interface must employ a flexible and easy-to-use command language

A specific bus architecture was not selected. The architecture used must be compatible with the processor and data bus selection. It will be desirable to select a data bus protocol that allows any processor to talk to any other without dependence on a master bus controller. This suggests a contention rather than polling protocol. Like the architecture, the protocol selection must be compatible with the processor selection. Processors now in development include inter-processor communications features that must be considered in protocol selection. A recommended approach to system redundancy and safety is as follows:

- o Redundant or bypass bus architecture
- o Control and communications functions in HM-1 backed up by HM-2
- o All processors operable stand-alone for critical functions
- o Critical processors redundant with self-check
- o All software backed up by non-erasable mass memory

A fiber-optic data bus was selected as the baseline for interconnection of the SOC processors. This provides a high degree of EMI immunity and capability of growth to high data rates. Bus data rates have not been estimated, but indications are

that they will not be beyond the capability of shielded twisted pair technology. The choice of fiber-optics was primarily motivated by a desire for large margins over probable actual rates.

Specific processors and language were not selected. Present indications are that 32-bit microprocessors now in technology development and the new DoD ADA high-level language will be the logical selections for SOC. If this new technology progresses as expected, substantial software cost savings will be derived from its use.

Subsystems Interrelationships

The SOC subsystems interrelationships are summarized in Table 1. These interrelationships are, in general, simple and linear. The development of the subsystems and their associated software should be able to proceed largely independently with a minimum of integration difficulty. Well-developed specifications and interface controls, of course, are necessary to ensure trouble-free integration.

All subsystems, as well as the crew, depend on adequate operation of the EC/LSS and electrical power subsystems. These are therefore critical. Appropriate attention was given to their degraded-mode capabilities.

3.3 GEO SOC

Modifications of the SOC design needed to operate at geosynchronous orbit were analyzed and defined. The resulting configuration is presented in Figure 31. The GEO SOC was viewed primarily as a satellite servicing facility. It was estimated to need a crew of four. The principal modifications needed are the following:

1. A composite shield for the electron-bremmstrahlung environment. A polyethylene (or similar hydrocarbon material) outer shield would be used to absorb the electrons. An inner high-Z shield would attenuate the bremmstrahlung radiation. The most practical means of implementing the

		INPUT FROM						
		POWER	TRACKING & COMMUNICATIONS	EC/LSS & THERMAL CONTROL	FLIGHT CONTROL	PROPELLION	CONTROLS/ DIS & MAIN PROCESSOR	CREW
INPUT TO	POWER	—	Ground Commands*	Thermal Control	None	None	• Power Switching Requests	• Manual Backup Operation
	TRACKING & COMMUNICATIONS	Power	Ground Commands*	Thermal Control	Status	None	• SOC Data	• Audio & Video Comm • Backup Op
	EC/LSS & THERMAL CONTROL	Power	Ground Commands*	—	None	None	• Autonomous Operation Overrides	• Manual Backup Operation
	FLIGHT CONTROL	Power	• State Vector Updates • Attitude Commands	Thermal Control	—	Execution Verification	• Flight Control Overrides	Manual Backup Operation
	PROPELLION	Power	None	Thermal Control	Thrust Commands	—	• Manual Thrust Control	None
	CONTROLS, DISPLAYS, & MAIN PROCESSOR	• Power • Status Data	• Data Updates • Software Updates	• Thermal Control • Status Data	• Status Data	• Status Data	—	• Normal Control & Data Inputs
	CREW	• Lighting	• Audio & Video Communications	Thermal Control & Life Support	None	None	• Status Displays • C&C Data • Scheduling	—

*During Unmanned Periods, e.g. Buildup

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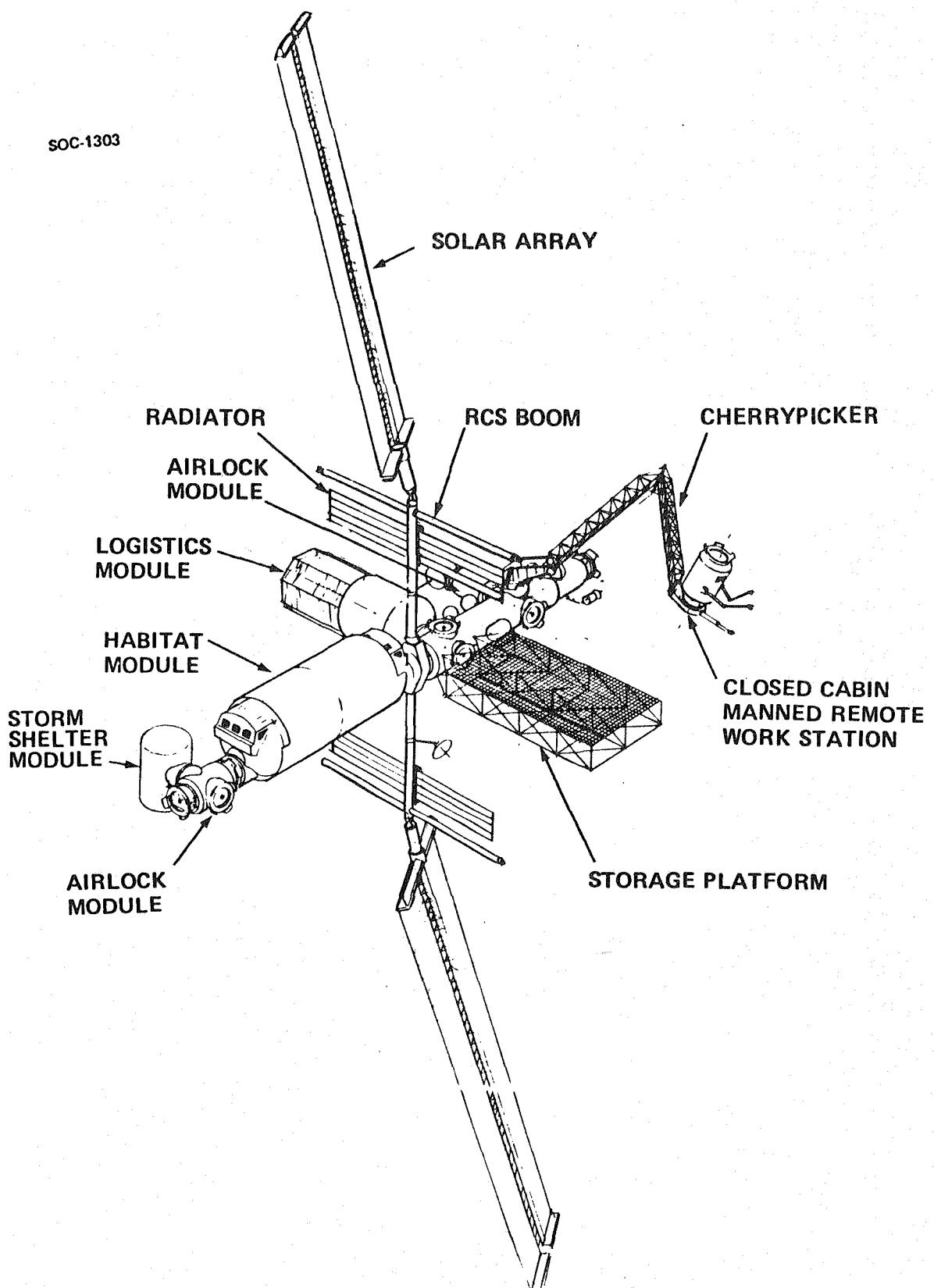


Figure 31. GEO SOC Concept

high-Z shield appears to be to make the SOC pressure shell skin from tantalum.

2. Modification of the Service Module to incorporate two solar array masts. This is practical because (a) the mast may be much shorter, and (b) the solar arrays can be much smaller.
3. Addition of a solar flare radiation storm shelter. Incorporating a shelter in the habitat module was investigated. A separate shelter appeared to be more practical, but this needs further assessment. This storm shelter is heavily-shielded and must support the crew for periods up to about a week if a major flare occurs. Ordinary flares would require the crew to occupy the shelter for one or two days.

3.4 USES OF THE EXTERNAL TANK

Use of the external tank was investigated for (a) propellant storage, and (b) a pressurized hangar. It was found that the ET insulation and thermal design is not suitable for long-term containment of cryogenics. The needed modifications are so extensive that design of a new tank would be less expensive. The volume needed is far less than that of the ET. Propellant storage tanks designed for this use would be far smaller than the ET and could be delivered to the SOC in the Shuttle payload bay.

Minor modifications of the ET would permit its use as a pressurizable hangar. The need for a pressurizable hangar is uncertain, but if such a need is confirmed, modification of an external tank appears to be the most straightforward way of meeting it. A representative SOC-ET configuration is shown in Figure 32.

FEATURES

- NO TANK WALL CUTS EXCEPT END DOME
- OTV TRANSIT PATH STRAIGHT OUT OF HANGAR
- LOCATED IN FLIGHT SUPPORT AREA

DISADVANTAGES

- OBSTRUCTS 2 BERTHING PORTS
- LO₂ TANK NOT READILY ACCESSIBLE BY IVA

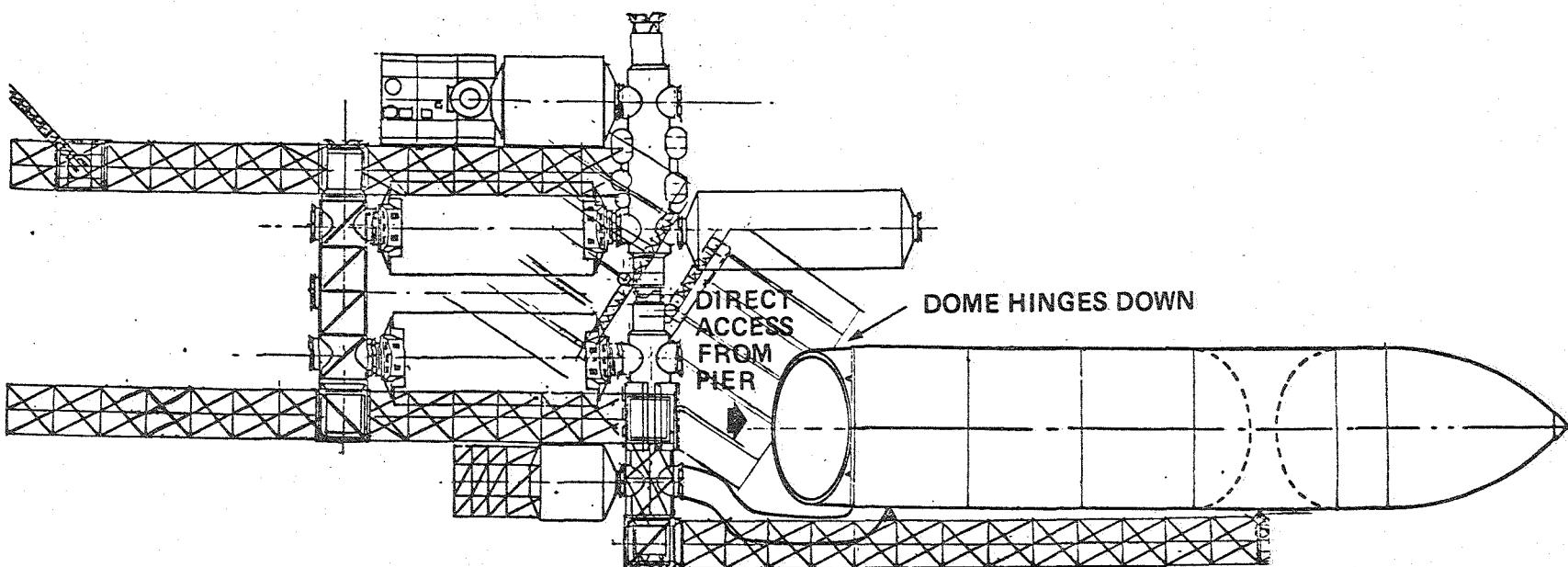


Figure 32 SOC/ET Configuration 1—ET on Pier Centerline

4.0 PROGRAMMATICS

This section presents a summary of the program analyses developed for the Space Operations Center. Additional information is provided in a companion document, D180-26785-2, "Programmatics and Cost."

4.1 COST AND PROGRAM OPTIONS

Program analyses for the Space Operations Center were built upon cost and schedule analyses. Cost estimating was done by parametric methods, using the Boeing Parametric Cost Model (PCM). Schedule estimates were developed by analogy with similar programs, using automated network analysis tools for representative system elements.

The Boeing PCM uses historical correlations to develop estimates of the labor required to design and manufacture system hardware. The model emulates the Boeing organization by allocating labor estimates to generic functions such as engineering, development shop, manufacturing, software, quality control, and so forth. This model structure has two advantages: first, its alignment with functional organizations allows its results to be compared with classical "grass-roots" estimates; and second, calculating in labor hours rather than dollars substantially improves ability to correlate with historical data. This second advantage is especially true in these days of severe inflation and rapid fluctuation in labor rates.

PCM is designed to operate at the subsystem element level. Typical entries are items such as RF amplifiers or berthing ports. Thus, a typical cost run for an SOC module involves more than one hundred item entries. For each item, a physical descriptor such as weight, with estimates of design complexity and numbers of items to be produced, is entered.

For the SOC program analyses, we used PCM to develop lump-sum costs for each system module. Modules and associated costs were then allocated to program phases. Schedule projections were used to estimate the periods over which costs would be spread. Cost spreading beta functions were then used to develop estimates of annual funding requirements for the various candidate programs.

An evolutionary development concept was created for the SOC reference design. This program exhibited relatively rapid funding profile buildups and high peak funding because two primary system modules, the habitat and service modules, had to be developed before a working space station could be placed into orbit. Figure 33 displays an example of the funding profile required to implement the reference program.

This funding problem was inherent in the reference system design. Its resolution required a change in design approach. Significant reduction in the peak funding required to establish an initial space station could only be achieved by developing a module design that incorporated all the essential features of a small space station in a single module. Retention of the capability to grow to a highly-capable Space Operations Center dictated that the initial module be adaptable to the overall SOC design approach.

These considerations highlight the importance of establishing an overall system and program design at the outset of a space station program. While it may be necessary to leave out desirable system features in the beginning of a program, it is essential that they be merely left out, not designed out. The design of a space station is much like the design of a house, i.e., not like the design of an airplane or launch vehicle. A great deal of growth potential can be designed into the system if properly planned from the beginning.

The habitable service module design approach for the Space Operations Center offers the establishment of an initial space station at less cost than the reference approach. Only a single module need be developed for the initial system. The structural system of this module can be adapted to serve as a resupply module. Two of the habitable service modules joined together provide an initial space station that can house four people with adequate redundancy. This configuration is illustrated in Figure 34.

Later, as mission needs for more crew and additional capability arise, habitat modules can be added to the initial configuration. Since the habitable service modules can house four people, the resulting operational SOC can house twelve people in comfort. If the service module structure is used for a docking tunnel as illustrated in Figure 34, a generous amount of laboratory space is available in the

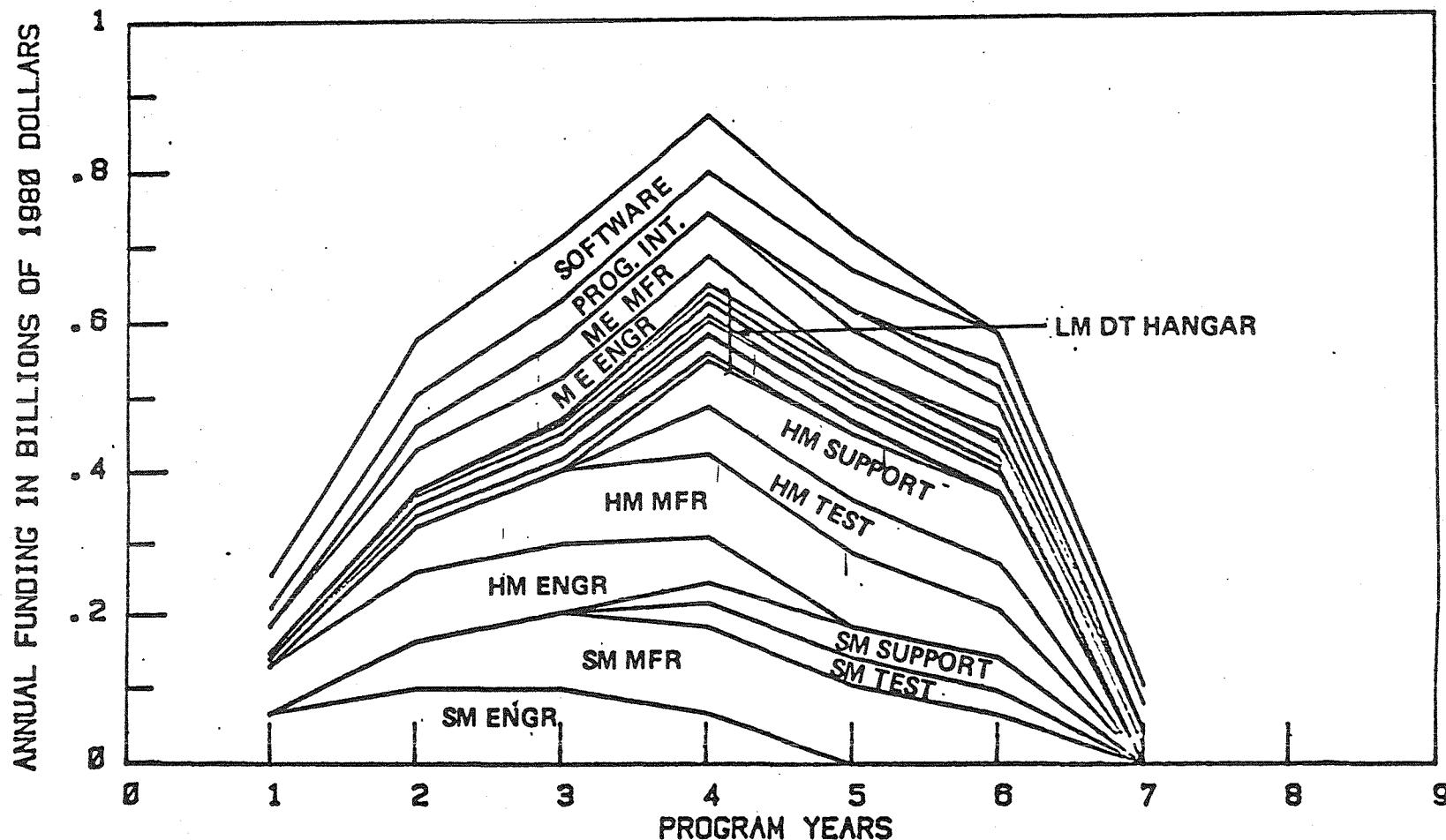


Figure 32. SOC Reference Program Funding

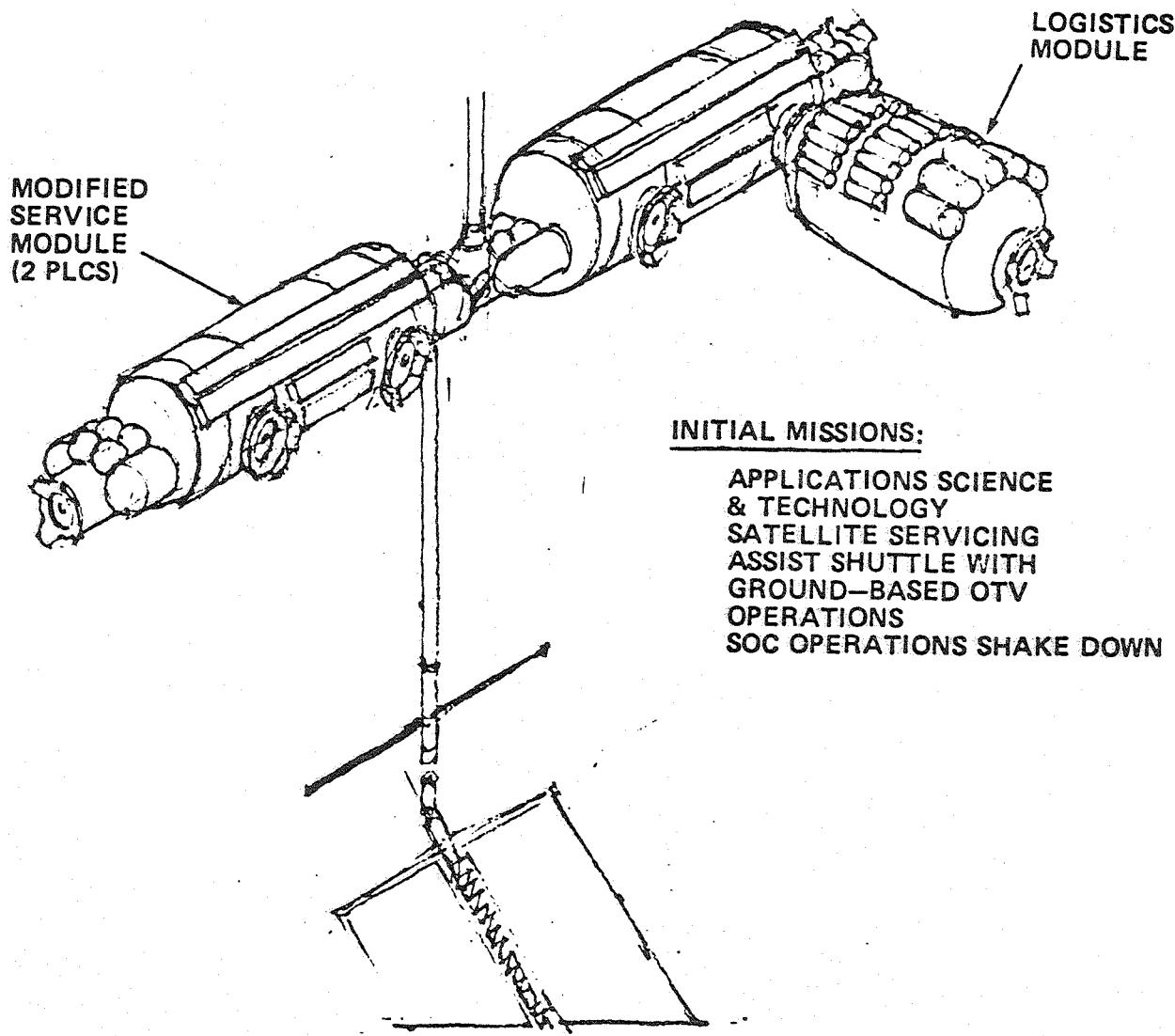


Figure 34. 4-Man SOC Concept

operational SOC. Table 2 presents a cost summary for this program. A funding profile estimate for this development approach is shown in Figure 35.

The initial system can be made somewhat more austere by (1) deferring the control moment gyros, the CO₂ reduction system, and the potable water processing unit, and by initially procuring only the amount of solar array needed to operate the initial station. Software development can be held to bare essentials. NASA laboratories can be used for part of the system integration testing. By these cost-saving measures, it is estimated that the initial SOC can be established at a total contracted cost less than two billion 1982 dollars. The cost-saving measures recommended do not inhibit the growth potential of the system. The increased capability of the initial habitable service modules offers an eventual SOC system with more capability than the original reference system.

4.2 SOC COST/BENEFIT COMPARISON

SOC costs for research and development, and for investment and operations, were analyzed and compared with estimated benefits. Details of the analysis and results are presented in the Cost and Program Summary. The main conclusions are:

1. The capability advancements and cost reductions made possible by development of a Space Operations Center and an advanced-technology space-based upper stage can be expected to attract more than enough additional space traffic to U.S. services to amortize SOC research and development.
2. The estimated economic benefits derived from use of the SOC as a research and applications facility are adequate to amortize and offset investment and operations costs.
3. The cost savings for flight support, construction operations, and satellite servicing are clear benefits beyond those needed to offset costs.
4. Intangible benefits were not estimated, but clearly exist. Examples include: focus for the U.S. space program; stimulus for education in technical and

Table 2 Elements of Cost - Modular Evolutionary Program

	INITIAL (4 CREW)		OPERATIONAL (12 CREW)		GROWTH (CONSTR. EQUIP. ADDED)	
	DDT&E	PRODUCTION	DDT&E	PRODUCTION	DDT&E	PRODUCTION
MODIFIED SERVICE MODULES	684	564				
LOGISTICS MODULES	106	158				
HABITAT MODULES			550	450		
DOCKING TUNNEL			70	80		
AIRLOCKS	30	50				
HANGARS	70	25		25		
SUPPORT EQUIPMENT	22	76	275	195	25	15
OTV SPACE-BASING EQUIP			200	150		
CONSTRUCTION EQUIP			25	15	250	150
SOFTWARE	150		150		90	
BUILDPUP SUPPORT	50	75	100	120		
NO. OF SHUTTLE FLIGHTS		(3)		(6)		(2)
SUBTOTALS	1112	948	1370	1035	365	165
TOTALS	2060		2405 ADDED; TOTAL \$ 4465		530 ADDED; TOTAL 4995	

NOTES:

- 1) COSTS ARE 1980 DOLLARS IN MILLIONS
- 2) SHUTTLE LAUNCH COSTS NOT INCLUDED
- 3) LEVEL I PROGRAM INTEGRATION COSTS NOT INCLUDED

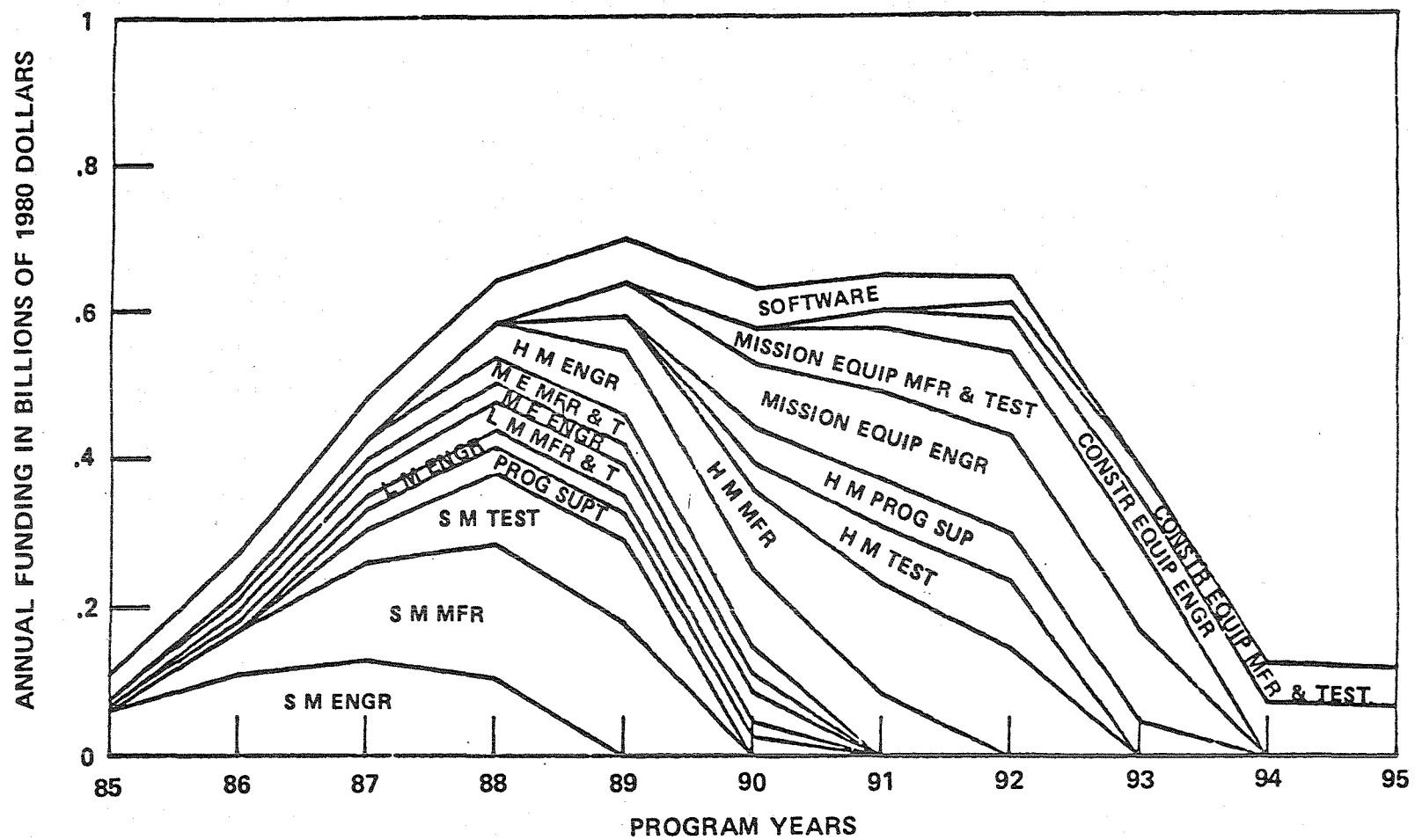


Figure 35. SOC Evolutionary Program
Development Funding Keyed to Mission Needs

scientific fields; U.S. space leadership; and potential defense applications of manned platform technology.

4.3 PROGRAM RECOMMENDATIONS

4.3.1 Pre-Phase B

Further study of the evolutionary system development approach, using a habitable service module, is warranted. In addition, there is a near-term need for additional analysis and definition of key SOC subsystems. This can be done with confidence that the results will be applicable to the system design that is developed in Phase B; the technical definitions of these subsystems are nearly independent of specific mission applications and are relatively independent of configuration. These studies could provide valuable technical inputs to Phase B and probably shorten the time needed to conduct a Phase B preliminary design. Specific recommended subsystem studies are as follows:

Comparative design definition of battery and regenerative fuel cell electric power systems—Preliminary studies, have indicated significant advantages for the regenerative concept, in which high-pressure electrolysis units are used to regenerate reactants from water. A comparative design study in greater depth is needed to make a final selection. This study should also investigate design integration of the solar array masts. These masts will be quite complex, carrying electric power, data, thermal control, propulsion, and communications services. They must be deployed when the electric power section or service module for the SOC is launched.

Data management and software systems analysis—Studies to date have indicated a strong preference for advanced technology microprocessors, and a federated processing system architecture. The new standard DoD high-level language, ADA, offers great promise for reducing software costs. A systems analysis and design study should be carried out, including high-level preliminary design of software elements needed early in the program, integration of displays and controls considerations, and selection of a specific architecture and communications protocol. Even though the architecture might be changed later in Phase B, the

results of this pre-Phase B study would be invaluable as an input, allowing the Phase B study to immediately get to design specifics.

Flight control and dynamics analysis—This study would have to use representative configurations, but the results would be generally applicable to other configurations in the SOC class. Dynamics modeling is needed to develop the requirements for technology advancements in adaptive control and flight control systems. The dynamics modeling should include analysis of zero-g slosh dynamics associated with cryogenic propellant storage for orbit transfer vehicles.

Communications system analysis—An analysis, conceptual design, and technology assessment should be made for millimeter-wave communications systems and traffic control radar. Needs for high data rates and immunity from RFI can best be met by millimeter-wave systems.

4.3.2 Phase B

Phase B studies should be vertically-integrated, even though later procurements may be implemented as separate contracts for each SOC module. The vertical integration, i.e. preliminary design of the entire system, is necessary to obtain the proper understanding of system, subsystem, and operational interrelationships. Phase B should concentrate on the modules to be developed first, but should render sufficient design detail on later modules that all interfaces are thoroughly understood, and so that specifications can be written for the later modules without resort to further Phase B study.

4.3.3 Development

The alternate system option is recommended for development, rather than the reference design. The alternate system better meets presently-identified mission needs and is more compatible with expected funding capabilities.

Development of the SOC and of an advanced-technology orbit transfer vehicle should be coordinated. Both are needed to satisfy forecast mission needs. Transition to space-based operation of the orbit transfer vehicle should occur as soon as practical, but initial operation should be ground-based to (1) develop

operational experience with the vehicle, and (2) allow time for development of efficient zero-g propellant transfer and management systems.

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